WHITE PAPER

SALMONID TRAVEL TIME AND SURVIVAL RELATED TO FLOW IN THE COLUMBIA RIVER BASIN

Northwest Fisheries Science Center
National Marine Fisheries Service
2725 Montlake Boulevard East
Seattle, Washington 98112

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CONTENTS

FORWARD

The purpose of this white paper is to provide a synthesis of scientific information regarding the effects of river flow through the hydropower system, as it is presently configured and operated, on anadromous salmonids. Other white papers are available that address the effects of predation and dam passage on salmonids. A fourth white paper provides a synthesis of scientific information on the effects of transporting juvenile salmonids around dams to mitigate for losses of juvenile migrants that would otherwise migrate downstream through the dams on the lower Snake and Columbia rivers. These papers are available on the Northwest Fisheries Science Center home page (www.nwfsc.noaa.gov/pubs/nwfscpubs.html).

The white papers do not address the possible effects on salmonids that might accrue from major changes to the present configuration of the hydropower system (e.g., draw down or dam removal); nor do they speculate about potential indirect effects (e.g., delayed mortality) that might occur as a result of hydropower system passage. Empirical data on these subjects are scarce. Other forums, such as the Plan for Analyzing and Testing Hypotheses (PATH) and the Cumulative Risk Initiative (CRI), are addressing these issues. Nonetheless, it is recognized that many of the impacts of dams on migrant fish, as identified in the white papers, would decrease with removal of dams. Most analyses conducted to date indicate that removal of dams would lead to higher direct survival of migrant fish. Such findings are not inconsistent with anything presented in this white paper.

Following regional review beginning in October 1999, this white paper has been modified to reflect comments and information provided by numerous reviewers and resource agencies including Idaho Water Users Association, Inc., IDACORP, Inc., Oregon Department of Fish and Wildlife, U.S. Fish and Wildlife Service, Idaho Department of Fish and Game, Columbia Basin Fish and Wildlife Authority, Washington Department of Fish and Wildlife, Columbia River Inter-Tribal Fish Commission Center, and Fish Passage Center.

INTRODUCTION

Known world-wide for its anadromous Pacific salmon and steelhead, the Columbia River Basin now has many stocks at critically low levels, and most of these stocks are listed as threatened or endangered under the Endangered Species Act (ESA). Although overfishing had substantially depleted some stocks by early in the 20th century, direct and indirect losses due to environmental modification have had the greatest, long-term effect on stock viability (Williams 1989). Some of the largest losses resulted from dam development (Raymond 1988, Williams 1989, NMFS 1991). Deleterious effects of dams are numerous. Dams block access to historic spawning areas, cause direct and indirect losses to fish (both juveniles and adults) that pass through them, and form reservoirs that alter environmental conditions, resulting in new assemblages of species or increased habitat for existing species, including predators. Furthermore, dams alter the magnitude, timing, and quality of flow.

River flow in the Columbia River Basin has been altered substantially by the construction of 28 major dams used for storage and hydropower production. By 1979, the total storage capacity had reached nearly 40% of the Columbia River's annual discharge (Pulwarty and Redmond 1997). Spring runoff is now stored in large headwater storage reservoirs for use during periods of naturally low flows. In particular, hydroelectric system storage and regulation reduces river flows significantly during the spring and early summer months when juvenile salmon and steelhead are migrating downstream to the ocean (Table 1, Fig. 1.) A major consequence of dam development and reservoir storage on the mainstem Columbia and Snake rivers is a reduction in spring and early summer flows and an increase in cross-sectional area of the river, resulting in delays in downstream migration.

Since nearly 64 percent of the total storage capacity in the entire Columbia River basin is located in the upper Columbia River basin above Chief Joseph Dam, most of the change in the natural shape of the hydrograph at The Dalles Dam in the lower Columbia River is due to streamflow regulation and storage changes in the upper Columbia River Basin (Table 1.) The Snake River basin below Hells Canyon Dam has only about 7 percent of the total storage capacity in the basin. Accordingly, storage regulation changes are less pronounced in the lower Snake River than in the Columbia River.

Reservoirs created by dams have increased the total cross-sectional area of the river, decreasing water velocity and turbidity. These conditions have led to increased travel time for migrating smolts and subjected them to greater exposure to predators and other factors of mortality (Raymond 1979, 1988; Williams 1989). Moreover, the change from free-flowing river to a series of reservoirs substantially modified the river's thermal regime. The large mass of stored water (~ 48 million-acre-feet [Maf]) has created thermal inertia, making the river slower to cool in the fall, slower to warm in the spring, thus moderating temperature extremes. Through a variety of mechanisms, these flow-related environmental changes have affected the timing of salt-water entry for juvenile migrants. Fall chinook salmon (*Oncorhynchus tshawytscha*) from the Snake River Basin are particularly susceptible to changes in the thermal regime as they spawn and rear in the mainstem river. Further, delays in their migration due to slack water in impoundments

Table 1. Average monthly spring and summer flow (kcfs) at Priest Rapids, Ice Harbor and The Dalles Dams pre- and post-completion of Mica, Libby and Dworshak Dams (data from A.G. Crook Co. (1993); Fish Passage Center; and COE Annual Fish Passage Reports, 1973-98).

Project	Month	1928-72	1973[a]-98	Change
Priest Rapids Dam	May	213	156	-27%
	June	322	167	-48%
	July	228	136	-41%
Ice Harbor Dam	May	121	103	-14%
	June	110	101	-8%
	July	40	45	+13%
The Dalles Dam	May	344	268	-22%
	June	446	266	-40%
	July	278	176	-37%

[a] System storage increased greatly with the completion of Mica (1973 - 12 million acre-feet (maf) and Libby (1975 - 5 maf) Dams in the upper Columbia River basin and Dworshak (1974 - 2 maf) Dam in the Snake River basin.

place these juvenile migrants in reservoirs during periods when water temperatures approach chinook salmon's thermal maximum.

Direct mortality of adult migrants has been observed under high spill conditions, though direct losses of adults were not sufficient to affect the overall viability of chinook salmon stocks (Junge 1966, Merrell et al. 1971, Gibson et al. 1979). However, direct juvenile salmon mortality increased substantially after the construction of dams in the Snake River. Per-project survival in the 1970's was consistently measured below 70% and dropped to as low as 35% in one year (1973) (Raymond 1979, Sims and Ossiander 1981).

Concerns over rapid stock declines led Congress to pass the Northwest Power Act of 1980, establishing the Northwest Power Planning Council (NWPPC). Among the charges for the NWPPC were to develop and implement programs to offset the effects of dams on salmon. In

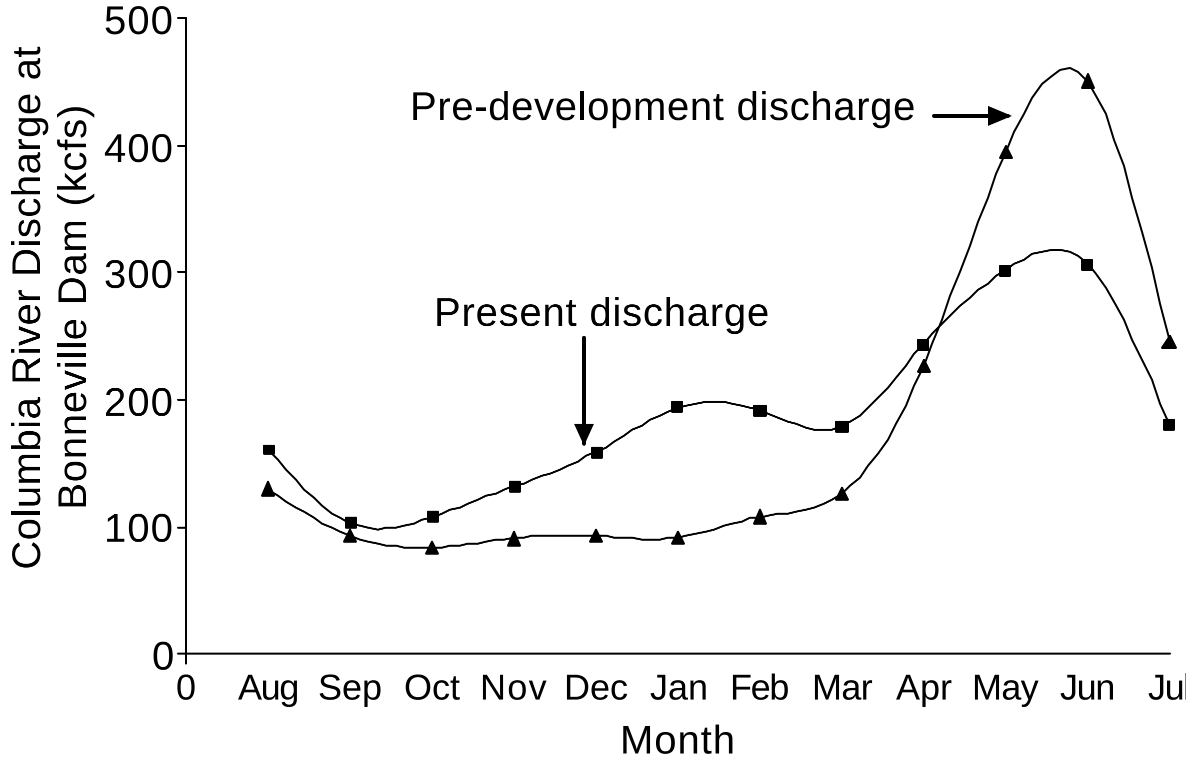


Figure 1. Average monthly flows at Bonneville Dam under present operating conditions of the Columbia River hydropower system compared to flows that would have occurred if no storage reservoirs were in place.

1982, the NWPPC issued its first Columbia River Basin Fish and Wildlife Program, which adopted a "water budget" for "flow augmentation." This program authorized a group of regional fish and wildlife managers to utilize a volume of water in federal storage projects on the Snake and Columbia Rivers to increase flows to benefit migrating salmon. In spite of modifications to flow from water budget usage, wild populations of salmon continued to decline during the 1980s, leading to the filing of petitions in 1990 to list Snake River salmon stocks under ESA. In November 1991, the National Marine Fisheries Service (NMFS) listed Snake River populations of sockeye salmon *(O. nerka)* as endangered, and in April 1992 Snake River spring/summer and fall chinook salmon were listed as threatened. In the last few years, 9 additional Columbia River Basin stocks of salmon and steelhead (*O. mykiss*) have been listed as threatened or endangered.

The NMFS is charged with protecting anadromous fish listed under ESA. Section 7 of the ESA requires NMFS to consult with federal agencies on actions that may affect the continued existence of listed species. In 1995, NMFS concluded a consultation with the U.S. Army Corps of Engineers (COE), the U.S. Bureau of Reclamation (USBR), and the Bonneville Power Administration (BPA) on operation of the dams and reservoirs that comprise the Federal Columbia River Power System (FCRPS). The NMFS (1995) Biological Opinion (1995 BiOp) concluded that the agencies' proposed operations jeopardized the continued existence of Snake River chinook and sockeye salmon and that the system was unlikely to meet the biological requirements of these species unless there were major modifications in the migration corridor to significantly improve survival. A series of immediate actions were specified in the 1995 BiOp to improve conditions for salmon survival in the interim while further studies were conducted and actions considered to ensure long-term survival and recovery of the listed stocks.

One action prescribed in the 1995 BiOp was to modify reservoir and dam operations to increase the probability of achieving specific seasonal flow objectives for the benefit of migrating juvenile salmon. These flow objectives (Table 2) were somewhat modified in 1998 (NMFS 1998) to extend protections to recently listed steelhead evolutionarily significant units (ESUs). The present flow-management program uses two strategies: (1) limit the winter/spring drawdown of storage reservoirs to increase spring flow and the probability of full reservoirs and (2) draft from storage reservoirs during the summer to increase summer flows. Under the first strategy, the FCRPS storage reservoirs are operated to ensure a high probability of water surface elevations within 0.5 ft of the flood control rule curve by April 10 and to refill by June 30. Prior to the 1995 BiOp, FCRPS storage reservoirs were routinely drafted well below these levels to maximize the hydropower generation during the fall and winter. To meet spring flow objectives occasionally requires reservoir drafting, but flow objectives are primarily met through limiting winter drafting and rates of reservoir refill. During the summer, FCRPS storage reservoirs are drafted as necessary, but not more than specified limits, to attempt to meet the summer flow objectives and to provide colder water.

Table 2. Flow objectives (kcfs) as established by NMFS (1995) and modified by NMFS (1998).

	Spring		Summer	
	Dates	Objective	Dates	Objective
Snake River at Lower Granite Dam	4/03 - 6/20	85 - 100[a]	6/21 - 8/31	50 - 55[a]
Columbia River at McNary Dam	4/20 - 6/30	220 - 260[a]	7/01 - 8/31	200
Columbia River at Priest Rapids Dam	4/10 - 6/30	135	NA	NA

[a] Varies according to water volume forecasts.

While dams affect salmonid survival in a number of ways, this paper focuses on how the present configuration of the hydropower system affects river velocity and temperature, and how river flow is managed in the Columbia River Basin to improve survival. As is discussed under the final section - SUMMARY AND MANAGEMENT IMPLICATIONS - removal of dams would favorably increase conditions for migrant juvenile salmon compared to conditions that presently exist.

PHYSICAL PROPERTIES OF WATER AFFECTED BY FLOW

Flow (also referred to as discharge) is defined as the rate a volume of water moves past a specified point. In the Columbia River Basin, the most common unit of measurement is 1,000 cubic feet of water per second (kcfs). Flow directly affects water velocity and indirectly affects water temperature and turbidity. These factors can in turn influence fish travel time and survival.

Water Velocity

Water velocity is determined by the area through which flow passes. For a given flow, mean water velocity is inversely related to the area through which flow passes; smaller areas result in greater water velocity. Water particle travel time (travel time = distance/average velocity) is inversely related to water velocity and directly related to area. Construction of the hydropower system changed water particle travel time, particularly during summer, low-flow periods (Fig. 2.) Before dams and resulting reservoirs existed on the Lower Snake River, average water depth (and therefore cross-sectional area) increased as flow increased. Thus, increasing flow did not produce proportional increases in water velocity. Under current hydropower operation practices, mainstem reservoirs are maintained at a relatively constant elevation, regardless of discharge, and water velocity varies more directly with flow than it did prior to dam development.

Water Temperature

In general, water temperature changes over time as a result of heating and cooling processes such as solar radiation, atmospheric convection, and conduction. Amount of temperature change is a function of volume of water and duration of the heating or cooling mechanism. Smaller changes occur in larger volumes and with shorter durations. Increasing flow has the effect of reducing the rate water temperature is changed because the volume of water is increased. However, in the specific case of flow management, increasing flow can have complex effects on water temperature. For example, if water used for augmentation is warmer than the receiving water, then flow augmentation will increase water temperature in the mixing zone, proportionate to the flow of the two water sources. However, in the summer, by increasing the total volume of water subject to solar and atmospheric heat inputs, the rate of temperature increase from the mixing zone downstream would decrease. If the augmentation water is cooler than the receiving water, water temperature of the receiving water is decreased through the mixing zone and the rate of temperature change is decreased by the additional volume of water subject to the heat input.

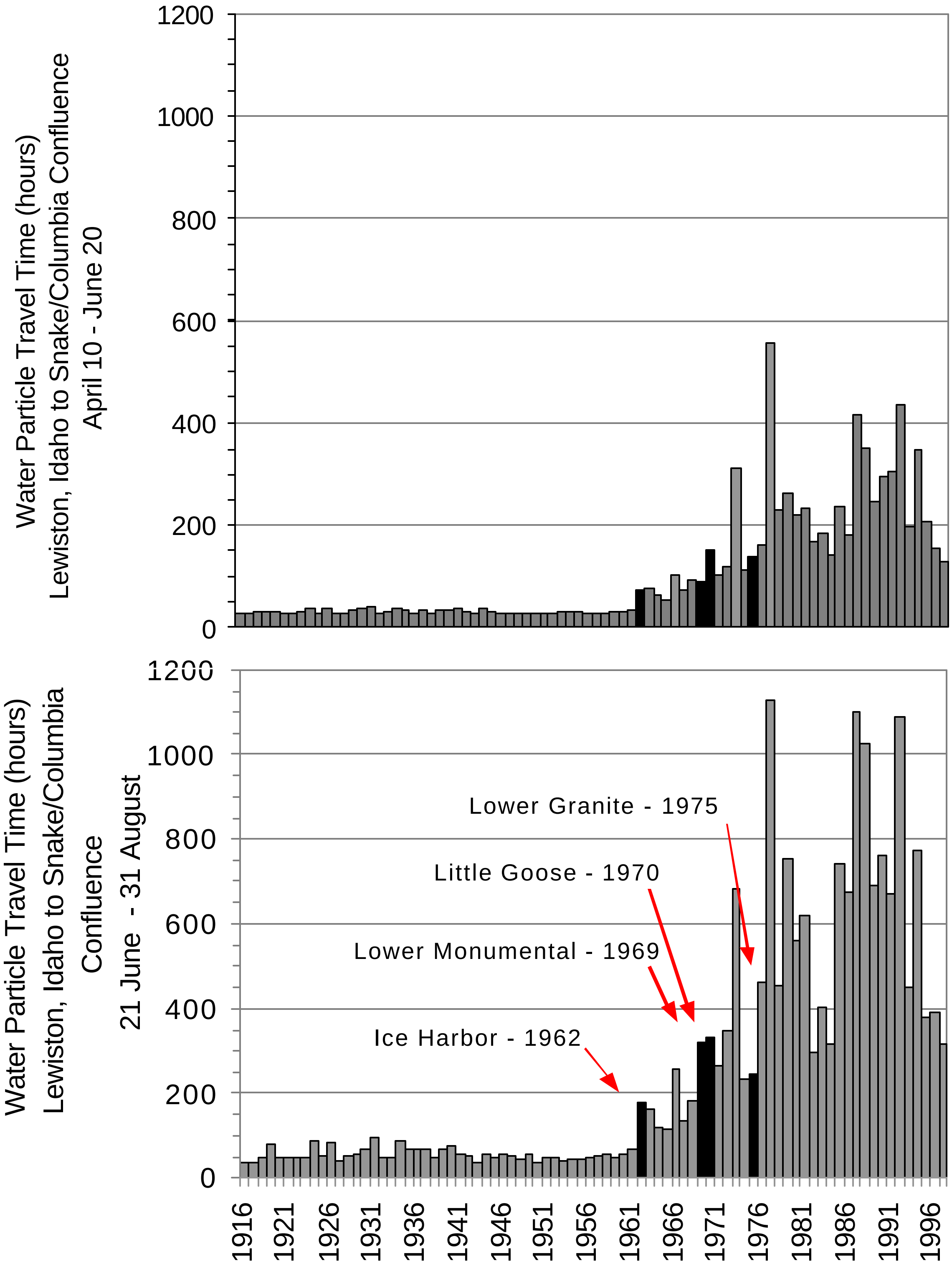


Figure 2. Estimated seasonal average water particle travel times from Lewiston, Idaho to the Snake and Columbia River confluence (after Dreher 1998).

Turbidity

Turbidity is a measure of light absorption in water caused by suspended matter. Regarding salmonid survival, turbidity is ecologically important because it influences, among other things, the depth to which photosynthesis occurs and visibility for sight-feeding fishes (Petts 1984). In natural streams there is generally a direct relationship between discharge and turbidity, although that relationship can change seasonally. Large reservoirs, particularly the storage reservoirs associated with the Columbia River hydropower system, greatly change turbidity and other seston(suspended particles) transport characteristics of rivers. Reservoirs function as large settling basins. They lower water velocities and turbulence, thus allowing larger solids to settle out of suspension. The high residence times of water within some reservoirs also afford an opportunity for processing the particulate organic debris component of the seston load. As a result, turbidity downstream from large reservoirs can fall to just a fraction of inflow turbidity (Soltero et al. 1973). Further, turbidity in downstream areas is generally the result of colloidal and buoyant materials that can remain in suspension for long periods. Also, because of the increased opportunity for photosynthesis (primary production) in reservoirs, it is not uncommon for seston loads downstream from large reservoirs to contain similar or even higher concentrations of organic matter than incoming waters (Lind 1971). In some cases, suspended organic matter may increase to several times that carried by the river upstream from the reservoir (Spence and Hynes 1971), and may even result in an increase in turbidity at times of low river discharge (Décamps et al. 1979). However, because the mainstem Snake and Columbia River dams are flow-through projects, their effect on turbidity levels is reduced (Ebel et al. 1989).

EFFECTS OF RIVER FACTORS ON MIGRATING JUVENILE SALMON

Flow and water temperature can affect migrating juvenile salmonids in many ways. Flow influences travel time, and consequently duration of exposure to mortality factors in reservoirs. Water temperature affects levels of physiological development and stress and influences factors directly related to mortality (e.g., predator metabolic rates). Flow and water temperature affect characteristics of the estuary and near-ocean environment and, through effects on travel time, the timing of estuary arrival of migrating smolts. The effect of each factor on overall survival likely varies among species and among years.

Flow can also affect levels of spill at dams which affects smolt travel time and survival. Spill can be forced (flow exceeds hydraulic capacity of the project) or voluntary. Voluntary spill has been used extensively since 1995 to reduce the proportion of smolts passing through turbines as prescribed in the 1995 Biological Opinion (NMFS 1995). Use of spill increases survival by passing greater numbers of smolts over the spillway, the route of passage with the highest survival. Spill can also reduce smolt travel time by reducing delay in forebays. The close relationship between spill and flow (high flow forces spill) confounds relationships among flow, travel time, and survival.

This section presents information on the response of migrating juvenile salmonids to varying river conditions. For each species, relevant studies are reviewed. In addition, a detailed analysis of recent PIT tag data for Snake River spring/summer and fall chinook salmon, and steelhead are presented. Results from the PIT tag studies are emphasized because they represent current conditions smolts face migrating through the hydropower system. The methods of this analysis are discussed below.

Methods for Analysis of Recent Pit Tag Data

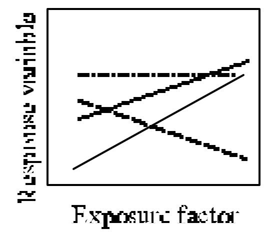
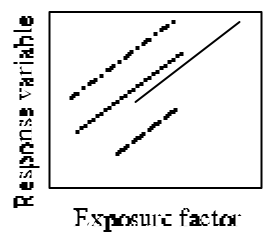
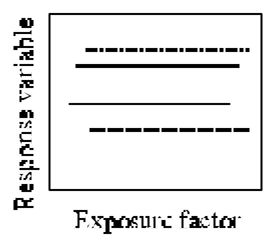
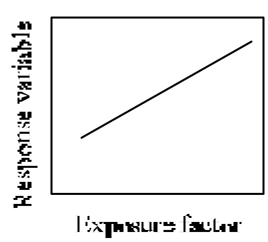
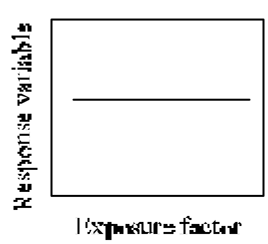
The analysis of recent PIT-tag data was based on methods presented in Smith et al. (1998, 1999), where more details can be found. Data from the migration years 1995-1998 were analyzed. For spring migrants, survival probabilities and travel times were estimated from release sites in the Snake River to McNary Dam. In earlier years (1993 and 1994), the PIT-tag monitoring system was not sufficiently developed to make estimates all the way to McNary Dam. Groups of PIT-tagged fish were released throughout the migratory season each year. Details of how groups were formed and over which river segments they were monitored is provided below for each species.

For each release group, estimates of survival and travel time were calculated, and the relationship between them and the exposure factors: flow, temperature, spill, turbidity, and in some cases, release date, were determined. In addition, it was determined whether the response of survival or travel time to these factors was consistent among years or whether year-to-year variability in the response could be detected. To detect potential year effects, a stepwise regression approach was implemented.

The stepwise regression proceeded by directly comparing three types of models for each combination of response variable (i.e., survival and travel time) and exposure factor. The first type of model, “common effects,” assumed that a single regression line was adequate to explain the response to the factor in all years. The “parallel effects” model assumed that the response to the factor (determined by the slope of the regression line) was the same among years but the overall level of survival or travel time (determined by the intercept) was different among years. Both the common effects and parallel effects models can have zero slopes, indicating no response to the factor. With the “unique effects” model, the response to the factor is different for all the years, requiring a separate slope and intercept for each year. A brief description of these models is contained in Table 3. Notice that for the common effects model, a single regression line appears in the plot. With the parallel effects model, four parallel lines (one for each year) appear in the plot. With the unique effects model, four lines with different slopes and intercepts appear in the plot.

The more complex year-effects models require more parameters. The stepwise regression method selects the “best” model based on the trade-off between decreasing the number of group. Specific details of the calculation of the exposure indices are provided below in the sections for each species.

Table 3. Description of models used in the stepwise regression of the PIT-tag data. Response variables are survival and median travel time; exposure factors are flow, temperature, spill, turbidity, and release date. The number of parameters and plots are based on four years of data.

Model	Description	Parameters	Plot
Unique effects	Year effects with unique regression lines – response to factor is unique for each year.	8 total: 4 slopes and 4 intercepts	
Parallel effects with response	Year effects with common slope – response to factor is the same but overall level of survival or travel time different among years	5 total: 1 slope and 4 intercepts	
Parallel effects no response	Year effects but with zero slopes – no response to factor but overall level of survival or travel time different among years	4 total: 0 slope and 4 intercepts	
Common effects with response	Common slope and intercept for all years – response to factor is identical among all years	2 total: 1 slope and 1 intercept	
Common effects no response	Common intercept for all years with no response to factor	1 total: 0 slope and 1 intercept	

Spring Migrants

Relevant studies

A number of studies have supported the relationship between river velocity and migration rate of yearling chinook salmon and steelhead in the Snake and Columbia Rivers. Raymond (1979) estimated that migration rates of yearling chinook salmon and steelhead ranged from 24 to 54 km/day through the free-flowing Snake and Columbia Rivers versus 8 to 24 km/day after impoundment, depending on the level of flow. Berggren and Filardo (1993) conducted more detailed examinations of the relationship between travel time of yearling chinook salmon and steelhead migrating through various reaches of the Snake and Columbia Rivers and various factors including river flow. Among the variables they tested, average river flow explained the greatest amount of variability in smolt travel time for Snake River yearling chinook salmon and steelhead. The predictive value of their models was improved by an additional variable that represented an index of smoltification. For yearling chinook salmon and steelhead migrating through the mid-Columbia River, however, Berggren and Filardo found the relationship between migration travel time and river flow was weak or non-existent. These investigators attributed their failure to detect a flow travel-time relationship to the limited range of flows observed during the study. In the mid-Columbia River, Giorgi et al. (1997) investigated factors that influenced migration rates of PIT-tagged yearling chinook salmon, steelhead, and sockeye salmon. Flow was the best single predictor of travel time for sockeye salmon and steelhead in this reach, but not for yearling chinook salmon.

Zabel et al. (1998) analyzed PIT-tagged Snake River yearling chinook salmon and obtained a similar migration rate versus river flow relationship as Berggren and Filardo (1993). When Zabel et al. (1998) added a seasonal flow component (fish were more influenced by flow as the season progressed), the model was able to explain substantially more of the variability in the data. Further, Beeman and Rondorf (1994) found that direct measures of smoltification (ATPase level and condition factor) were important in determining migration rates of yearling chinook salmon and steelhead migrating through the Snake and mid-Columbia Rivers. They concluded that for yearling chinook salmon, the effect of river flow and level of smoltification were approximately equal in determining migration rate. These latter studies indicate that the effect of river velocity on migration rate of spring migrants is not static and likely has a seasonally-varying component.

Early studies on the survival of spring migrants indicated that a strong relationship between survival and river flow existed. In the Snake River, Raymond (1979) and Sims and Ossiander (1981) estimated lower annual average survival for yearling chinook salmon in years with lower average annual flow in the

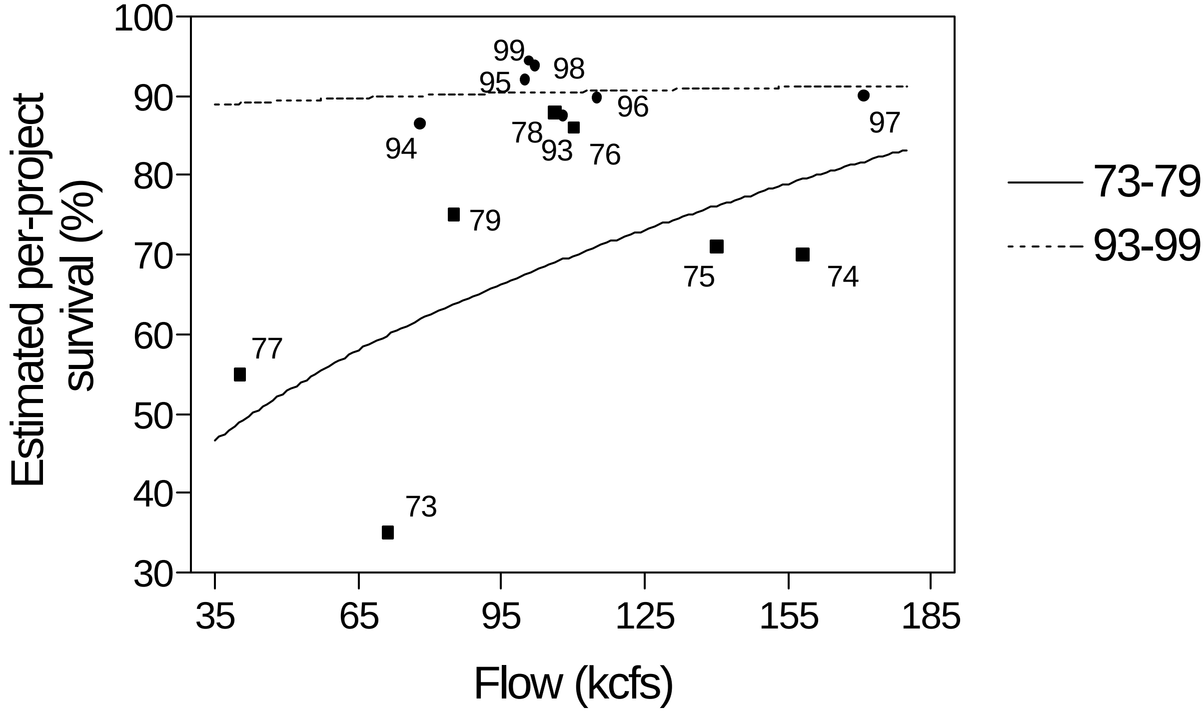


Figure 3. Historical and recent estimates of per-project survival (%) for yearling chinook salmon vs. index of Snake River flow (kcfs). Curves depict fitted nonlinear regression equations describing relationship between flow and survival in the two time-periods. Early period data from Raymond (1979) and Sims and Ossiander (1981).

years 1973-1979 (Fig. 3). Survival estimates were particularly low in drought years 1977 and especially 1973, when estimated per-project survival was only 35%. From these studies and others conducted outside the Columbia Basin, Cada et al. (1997) inferred a general positive relationship between flow and survival of downstream migrant salmonids within the hydropower system. Causative factors for this relationship are poorly understood, and different factors are likely to dominate in different flow ranges and in different years and for different groups of fish (ISG 1996). Further, river conditions and dam operations were substantially different in the 1970s (Williams and Mathews 1995), and it is unclear how the relationships observed in that time period apply to current conditions. Recently, Skalski (1998) found no correlation between yearling chinook salmon survival and daily flows or spill volumes in the Snake River.

Study design for PIT-tag analysis (1995-1998)

For spring migrants, release groups were formed at Lower Granite Dam. Fish PIT-tagged at Lower Granite Dam were grouped according to the day they were released into the tailrace, or for fish tagged above the dam, the day on which they were detected and returned to the river at Lower Granite Dam. Survival estimates and median travel times were calculated from Lower Granite Dam to McNary Dam. Study fish migrated through four projects: Little Goose, Lower Monumental, Ice Harbor, and McNary Dams.

Exposure indices of flow (kcfs), percent spill, and water temperature (°C) were calculated for each release group. The indices were calculated as the mean values measured at Lower Monumental Dam during the middle 50% of the group's passage. These indices measured at Lower Monumental Dam were found to reasonably represent conditions in the entire lower Snake River.

Travel time results for PIT-tag analysis

Correlations between the date of release and the exposure indices, and among the indices themselves, complicate interpretation of the results of analyses of effects on travel time and survival. Nonetheless, certain patterns are apparent. For yearling chinook salmon, the correlation between flow exposure index and median travel time was strong and the regression lines were relatively consistent from year to year (Table 4, Fig. 4). For steelhead, the correlation between flow exposure index and median travel time was slightly more variable than for yearling chinook salmon, though regression lines were fairly consistent from year to year (Table 5, Fig 5).

Smoltification levels of migrants passing Lower Granite Dam tend to increase through the migration season, so that release date is a rough index of smoltification level (Berggren and Filardo 1993, Zabel et al. 1998). In 1995 and 1998, for yearling chinook salmon and steelhead, the relationship between flow exposure index and date of release were great enough (flows generally increased throughout the season) to make independent assessment of the two variables difficult. Of the two variables for yearling chinook salmon, flow exposure was more highly correlated with median travel time in 1995, while release date was more highly correlated in 1998 (Table 4). For steelhead, median travel time was more highly correlated with release date than with flow exposure in both 1995 and 1998 (Table 5). In every case, when one variable was already in the regression model, adding the other variable did not significantly improve the model.

The correlation between flow exposure and release date was not as strong in 1996 and 1997. For yearling chinook salmon, both variables were significant predictors of median travel time when included together in multiple regression models for each year's data. For steelhead, both were significant in 1997, while only flow exposure was significant in 1996.

In multi-year analyses for both yearling chinook salmon and steelhead, the stepwise model selection procedure selected a unique regression line for each year for both flow exposure and for release date (Figs. 4 and 5 for flow exposure). For yearling chinook salmon, release date and flow exposure had virtually the same predictive value for median travel time (R^2 was 72.5% for release date, 71.1% for flow exposure). In multi-year models for steelhead, release date was a better predictor of median travel time than flow exposure (R^2 = 72.1% and 61.9%, respectively). Spill exposure and flow exposure were highly correlated for both species in 1996, 1997, and 1998.

Table 4. Summary of linear regression results for median travel time (Lower Granite Dam to McNary Dam) of daily release groups of yearling chinook salmon from Lower Granite Dam. (Based on Smith et al. 1999). For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2	P value	intercept	slope
Flow	1995	64.0	<0.001	22.51	-0.096
	1996	65.3	<0.001	19.78	-0.066
	1997	64.7	<0.001	20.82	-0.061
	1998	66.8	<0.001	26.41	-0.102
	all years (**1**)	71.1			
Spill %	1995	15.7	0.008	16.60	-0.199
	1996	53.1	<0.001	19.02	-0.237
	1997	61.6	<0.001	18.10	-0.226
	1998	26.9	<0.001	20.07	-0.232
	all years (**2**)	40.4			-0.229
Temperature	1995	21.2	0.002	20.41	-0.665
	1996	10.8	0.044	18.82	-0.803
	1997	38.6	<0.001	28.01	-1.623
	1998	56.0	<0.001	63.38	-4.091
	all years (**1**)	53.5			
Release date	1995	55.6	<0.001	29.34	-0.134
	1996	1.5	0.468	14.14	-0.024
	1997	62.1	<0.001	26.10	-0.130
	1998	80.4	<0.001	44.86	-0.258
	all years (**1**)	72.5			

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

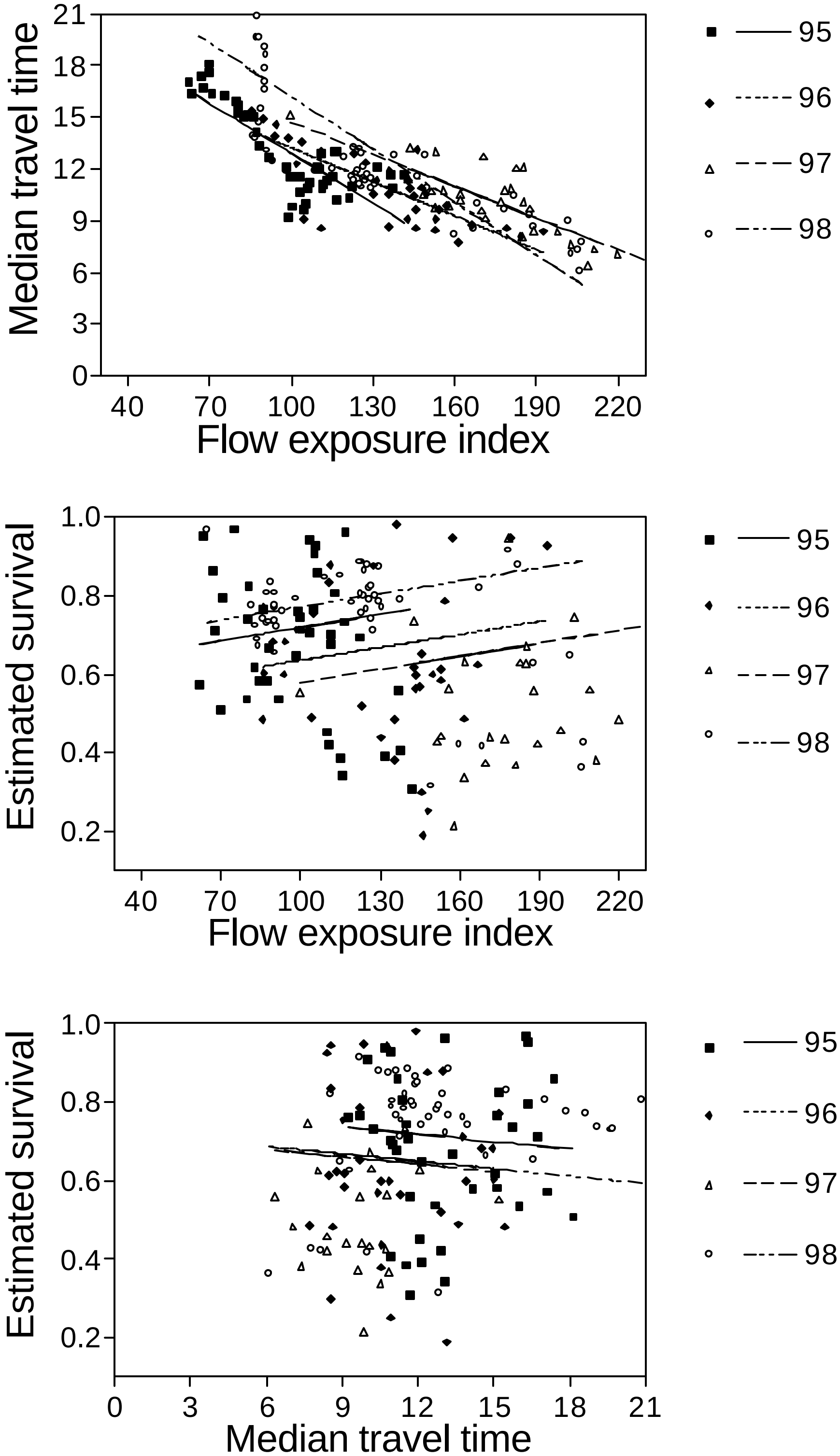


Figure 4. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and flow exposure index (kcfs) measured at Lower Monumental Dam, yearling chinook salmon, 1995-1998.

Table 5. Summary of linear regression results for median travel time (Lower Granite Dam to McNary Dam) of daily release groups of steelhead from Lower Granite Dam. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2	P value	intercept	slope
Flow	1995	15.6	0.056	16.18	-0.045
	1996	51.6	<0.001	16.05	-0.052
	1997	8.5	0.058	13.69	-0.031
	1998	68.4	<0.001	20.44	-0.080
	all years (**1**)	61.9			
Spill %	1995	4.2	0.336	13.70	-0.114
	1996	74.2	<0.001	18.16	-0.262
	1997	13.9	0.014	13.47	-0.148
	1998	32.9	<0.001	15.93	-0.199
	all years (**4**)	43.0	<0.001	15.82	-0.203
Temperature	1995	19.6	0.030	17.55	-0.557
	1996	7.7	0.169	17.94	-0.882
	1997	37.4	<0.001	21.10	-1.196
	1998	52.1	<0.001	48.81	-3.145
	all years (**1**)	52.0			
Release date	1995	56.4	<0.001	26.23	-0.119
	1996	22.9	0.013	22.29	-0.104
	1997	49.7	<0.001	20.68	-0.101
	1998	79.7	<0.001	36.13	-0.209
	all years (**1**)	72.1			

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

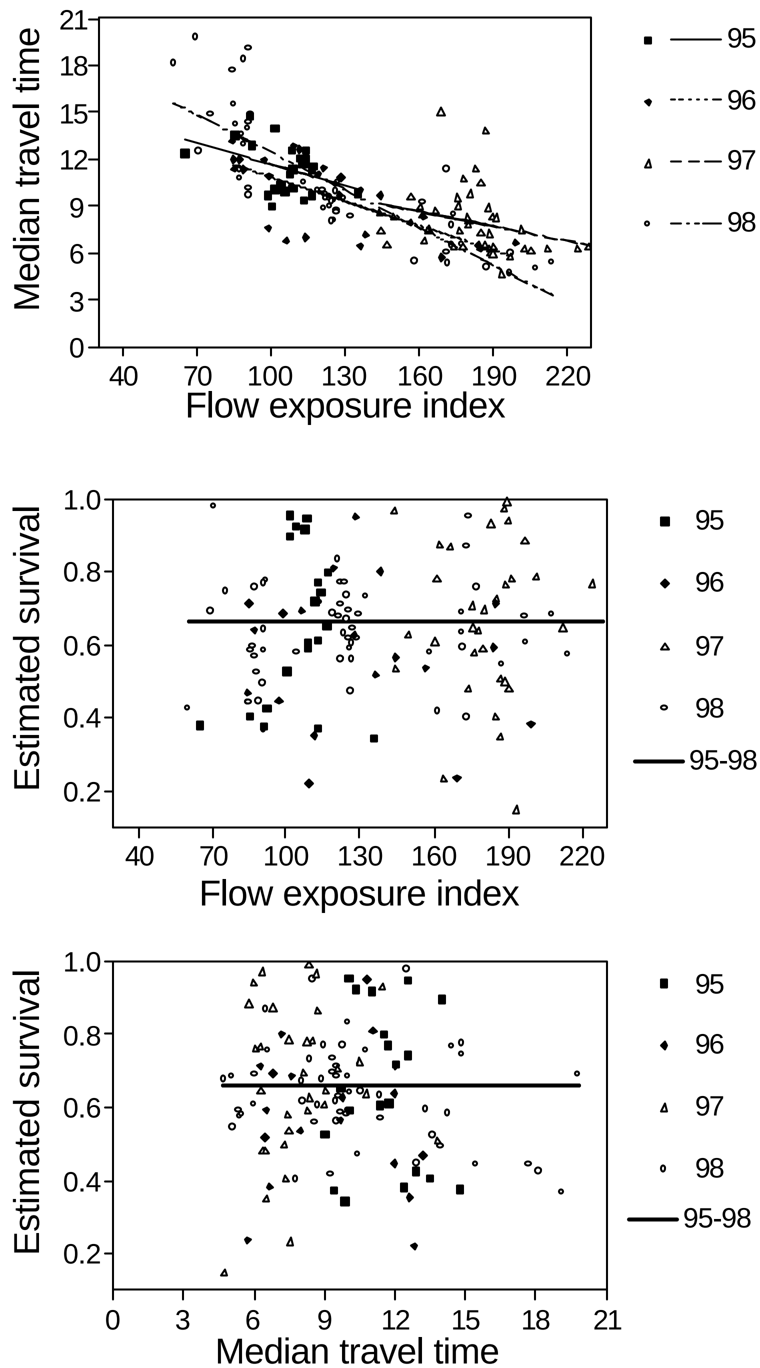


Figure 5. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and flow exposure index (kcfs) measured at Lower Monumental Dam, steelhead, 1995-1998.

Thus, significant correlations between spill exposure and median travel time may occur because both variables were correlated with flow exposure. Multiple regression models that already included flow exposure or release date were sometimes improved by adding spill exposure, but overall, the effects of spill exposure on median travel time appeared to be secondary to effects of flow and smoltification. The influence of spill on travel time may be greater at higher levels of spill (greater than about 20% of total flow) than at lower levels; when the spill percentage index was less than 20% or so, travel time was more variable (Figs. 6 and 7).

Survival results for PIT-tag analysis

For yearling chinook salmon, the correlations of estimated survival with flow exposure and percentage of water spilled were weak and inconsistent from year to year (Figs. 4 and 6, Table 6). Within single years, the correlation was significant only with flow in 1998 (Table 6). Between estimated survival and travel time, there was a nearly significant (P = 0.091) positive correlation (longer travel time, higher survival) in 1997 and a significant (P = 0.036) negative correlation (longer travel time, lower survival) in 1998 (Table 6). However, the R^2 values were so low as to have almost no predictive value, and the slopes were not significantly different, as the model selection procedure selected a model with parallel regression lines (R^2 = 15.0%) (Fig. 4). A model with parallel regression lines was also selected for the flow/survival relationship (Fig. 4), but as with travel time, the low R^2 value (15.0%) meant the model had little predictive value.

The correlations between steelhead survival estimates and flow and percentage of water spilled were also weak and inconsistent from year to year (Figs. 5 and 7, Table 7). The correlation was positive within some years and negative within others, but none of the correlations were significant (in 1995 is was nearly so; P = 0.078), but the range of observed exposures in that year was so narrow that the results did not appear reliable). Combining the points from all years resulted in R^2 of nearly zero between estimated survival and flow or spill exposure indices (Figs. 5 and 7). For the range of variables measured, none of the independent variables (flow exposure, spill percent exposure, temperature exposure, travel time, or date of release) had any statistically detectable effect on estimated steelhead survival

Conclusions for spring migrants

Smith et al. (1999) averaged survival estimates and flow exposure indices for PIT-tagged yearling chinook salmon for each year from 1995 to 1998 to compare with historical analyses of yearling chinook salmon survival (Fig. 3). In this analysis, no relationship was detected between per-project survival and observed flow conditions.

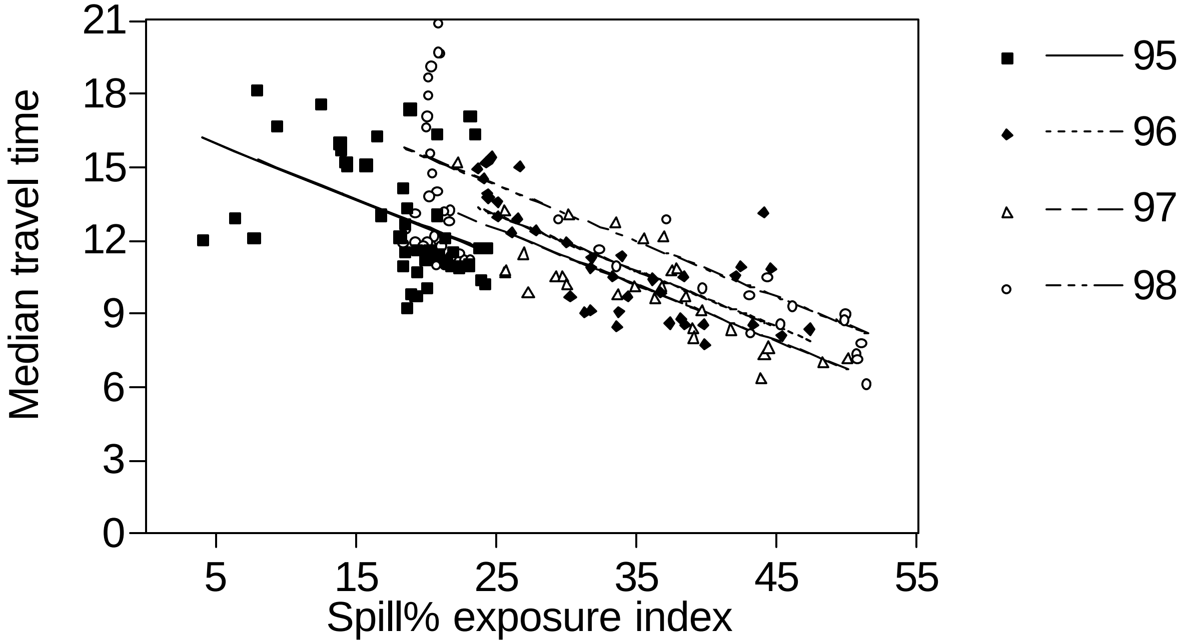
Despite a large database collected over several years using state-of-the-art fish tagging and analysis techniques, relationships between flow and survival and between travel time and survival for yearling migrants through impounded sections of the lower Snake River were neither strong (within- or

Table 6. Summary of linear regression results for estimated survival (Lower Granite Dam to McNary Dam) of daily release groups of yearling chinook salmon from Lower Granite Dam. (Based on Smith et al. 1999). For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2	P value	intercept	slope
Flow	1995	0.1	0.850	0.680	0.0004
	1996	4.8	0.188	0.514	0.0012
	1997	0.2	0.822	0.768	-0.0007
	1998	8.6	0.025	0.656	0.0011
	all years (**2**)	15.0			0.0011
Spill %	1995	3.7	0.210	0.530	0.0097
	1996	3.1	0.288	0.515	0.0045
	1997	0.0	0.952	0.630	0.0007
	1998	2.1	0.274	0.846	-0.0036
	all years (**3**)	10.9			
Temperature	1995	4.8	0.154	1.191	-0.0451
	1996	0.5	0.683	0.521	0.0135
	1997	7.9	0.141	2.124	-0.1354
	1998	9.5	0.018	0.444	0.0275
	all years (**4**)	10.4	<0.001	0.394	0.0313
Median travel time	1995	5.6	0.124	0.970	-0.0204
	1996	4.6	0.194	0.806	-0.0129
	1997	10.2	0.091	-0.043	0.0675
	1998	7.6	0.036	0.853	-0.0056
	all years (**2**)	15.0			0.0056
Release date	1995	0.2	0.759	0.592	0.0010
	1996	0.0	0.997	0.646	0.0000
	1997	7.7	0.146	1.804	-0.0095
	1998	8.8	0.024	0.535	0.0021
	all years (**2**)	14.0			0.0019

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)

5 = common effects no response (zero slope)



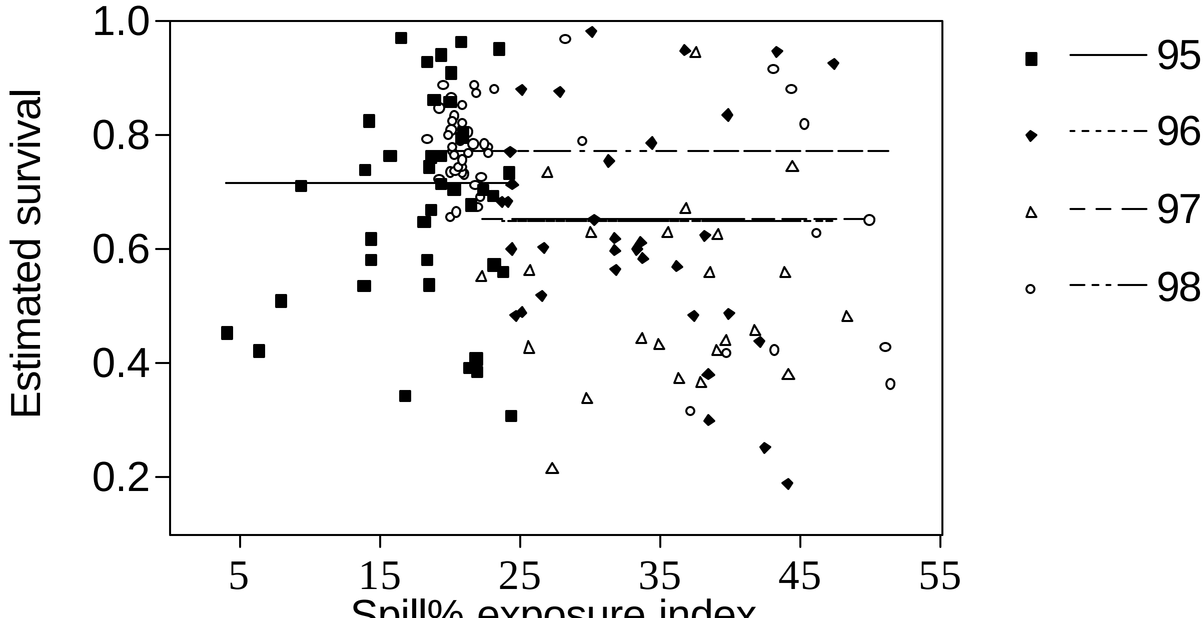


Figure 6. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and spill exposure index (percentage of flow spilled) measured at Lower Monumental Dam, yearling chinook salmon, 1995-1998.

Table 7. Summary linear regression results for estimated survival (Lower Granite Dam to McNary Dam) of daily release groups of steelhead from Lower Granite Dam. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2	P value	intercept	slope
Flow	1995	13.5	0.078	-0.138	0.0083
	1996	0.5	0.727	0.760	-0.0006
	1997	0.2	0.753	0.572	0.0009
	1998	0.2	0.765	0.669	-0.0002
	all years (**5**)	0.0			
Spill %	1995	5.1	0.290	0.015	0.0346
	1996	1.4	0.569	0.576	0.0034
	1997	0.8	0.561	0.527	0.0058
	1998	1.5	0.372	0.681	-0.0013
	all years (**5**)	0.0			
Temperature	1995	0.0	0.928	0.651	0.0081
	1996	2.1	0.481	0.188	0.0500
	1997	2.6	0.305	0.037	0.0654
	1998	4.2	0.132	0.169	0.0380
	all years (**5**)	0.0			
Median travel time	1995	1.3	0.594	1.049	-0.0270
	1996	6.1	0.225	0.898	-0.0237
	1997	2.3	0.332	0.411	0.0399
	1998	0.1	0.870	0.658	-0.0011
	all years (**5**)	0.0			
Release date	1995	4.9	0.301	-0.350	0.0089
	1996	0.2	0.810	0.489	0.0017
	1997	4.7	0.161	-0.264	0.0083
	1998	2.3	0.267	0.823	-0.0014
	all years (**5**)	0.0			

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

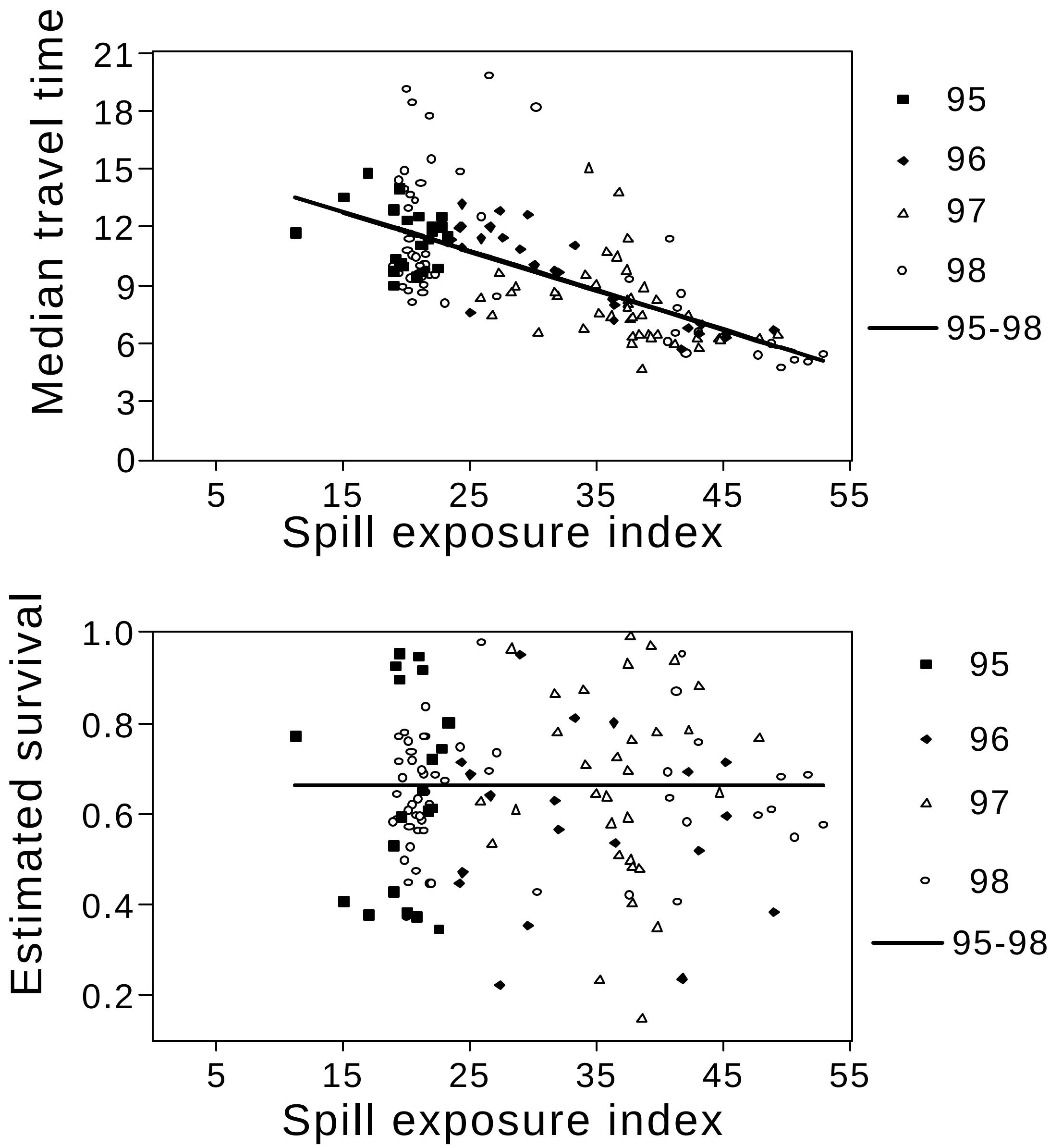


Figure 7. Relationships among median travel time (days) and estimated survival from Lower Granite Dam to McNary Dam, and spill exposure index (percentage of flow spilled) measured at Lower Monumental Dam, steelhead, 1995-1998.

between-years) nor consistent from year to year. Contrary to results observed in the 1970s under lower flow conditions (Fig. 3), the per-project survival of yearling chinook salmon and steelhead PIT tagged in 1993 and 1994 were substantially higher. However, analysis of the relationships among travel time, survival, and environmental factors over the longest reach possible (Lower Granite Dam to McNary Dam), did not include 1993 and 1994 because the PIT-tag interrogation system was not yet fully developed. During 1994, a spill program was implemented to improve the survival of yearling chinook salmon and steelhead, but not until 10 May, after the majority of fish had passed (spill occurred at Little Goose Dam throughout the 1994 season due to a lack of generation capability). Consequently, the years with the lowest per-project survival and lowest spill percent exposure (1993 and 1994) were excluded. An analysis that included the 1994 migration (but only estimating survival and travel time to the tailrace of Lower Monumental Dam) indicated that a significant relationship existed between spill percent and survival that was stronger than for flow in the combined year analysis (Smith et al. 1998). By maximizing the survival and travel time distance in an analysis of data from the 1995 through 1998 migration years (these years all had directed spill at dams as identified in the 1995 BiOp), the contrast in spill percent and survival was decreased, which may account for the lack of a significant relationship between the variables. In earlier studies, Sims and Ossiander (1981) found that spill had a more significant effect on survival than flow. Passing a higher proportion of smolts through spill decreases the number of fish passing through turbines, the dam passage route causing greatest direct mortality. In the years analyzed by Sims and Ossiander, passage conditions at dams were particularly poor (Williams and Matthews 1995), so their results are not surprising.

Previous attempts to quantify the relationship between flow and survival for yearling chinook salmon (Raymond 1979, Sims and Ossiander 1981) have correlated annual average survival with annual average flow. The analyses of recent PIT-tag data show that strong patterns in annual means suggested in historical data (Fig. 3) were not present within single migration seasons (Fig. 4, Table 6) or when survival estimates and flow indices were averaged annually.

A strong and consistent relationship exists between flow and travel time for spring migrants. Increasing flow decreases travel time. Thus, although no relationship has been detected within seasons between flow and yearling migrant survival through the impounded sections of the Snake River, by reducing travel times, higher flows may provide survival benefits in other portions of the salmonid life cycle and in free-flowing sections of the river both upstream and downstream from the hydropower system. Snake River basin fish evolved under conditions where the travel time of smolts through the lower Snake and Columbia Rivers was much shorter than presently exists. Thus, higher flows, while decreasing travel time, may also improve conditions in the estuary and provide survival benefits to juvenile salmonids migrating through the estuary or the Columbia River plume. By reducing the length of time smolts are exposed to stressors in the reservoirs, higher flows also likely improve smolt condition upon arrival in the estuary.

Estimates of survival using PIT tags only measure direct survival through a portion of the hydropower system. Conditions smolts experience during migration are reflected in the estimates of smolt survival, but the indirect effects, or delayed mortality (mortality caused by passage experience that occurs downstream from PIT tag detection sites) are not. Slower travel times could result in greater depletion of energetic reserves, reversal of smoltification characteristics, and greater exposure to disease. These factors could lead to delayed mortality not captured in current juvenile smolt survival studies.

Summer Migrants

Background

Subyearling chinook salmon exhibit more complex migratory behavior than do spring migrants. As “ocean-type” fish, they migrate downstream in the year they emerge. As they grow, they move toward the center of rivers, farther from the banks, and their rate of migration increases. Consequently, the relationships between survival and migration rate and factors such as flow and temperature can vary from year-to-year, depending on fish size and condition .

The presence of dams in the Snake and Columbia Rivers likely has substantially altered the migratory patterns for ocean-type chinook salmon. These fish typically spawn in larger rivers and initiate downstream migration as fry shortly after they emerge from the gravel. Ocean-type fry have reduced swimming ability (Thomas et al. 1969) and undergo greater downstream displacement than do stream-type fry (Taylor and Larkin 1986, Taylor 1988). Mains and Smith (1964) observed downstream migrations of fry (generally less than 70 mm in length) during March, April, and May in the free-flowing Columbia River just above the confluence of the Snake River and in the free-flowing Snake River below the confluence with the Clearwater River. During pre-impoundment periods, it is likely that fish were swept by spring flows to the estuary, where they continued to rear. Estuarine rearing has been observed in many stocks of ocean-type chinook salmon from the Sacramento River to the Nanaimo River. In the current river configuration, ocean-type chinook salmon originating from the Snake River, Hanford Reach, or Upper Columbia encounter slack water in impounded reservoirs and hold up to rear to the smolt phase before they continue to migrate volitionally. Subyearling chinook salmon measured at McNary Dam on the Columbia River and at Lower Granite Dam on the Snake River are typically 100-140 mm in length, indicating that they have undergone considerable rearing in the reservoirs. Park (1969) observed that after the completion of dams in the upper Columbia River, downstream migration of subyearling chinook salmon extended through August, where previously it was completed by July (Mains and Smith 1964). Thus, it appears that a major effect of dams on subyearling migrants is a shift in rearing from the estuary to reservoirs and extended residence in mainstem rivers.

A further consequence of the impounded river system is that seasonal temperature regimes have been altered, which affects the timing of spawning and emergence. In the Snake River, the thermal regime downstream from Hell's Canyon Dam has been altered as water temperatures are now warmer in the fall and cooler in the spring (Ebel and Koski 1968). Changes in water temperatures downstream of Brownlee Dam delay adult spawning in the fall and emergence and fish growth in the spring. A strong relationship exists between median passage date at Lower Granite versus mean temperature in the Snake River (Fig. 8), indicating that processes regulating maturation through the smolt phase are under temperature control.

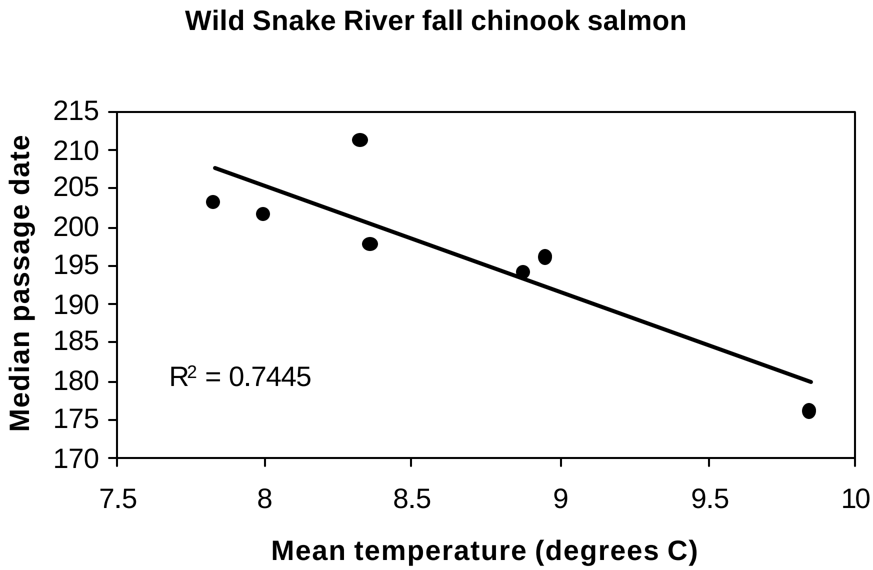


Figure 8. Median passage date at Lower Granite Dam versus mean temperature (degrees C) for wild Snake River fall chinook salmon. Passage date was based on the Passage Index. Temperature was recorded at the Anatone gauge in the Snake River. The mean was

Relevant studies

Berggren and Filardo (1993) found a significant flow/travel time relationship for wild and hatchery subyearling chinook salmon in John Day reservoir (Lake Umatilla). Flow alone was significantly correlated ($P < 0.01$), but was a poor predictor of travel time (R^2 = 28%). Inclusion of the range of flows encountered during migration and the date of entering the index reach markedly improved the predictive capability of the model (R^2 = 65%). The date at which salmon entered the reach was likely a function of fish development and smoltification.

Regression of travel time (from release as pre-smolts in the free-flowing Snake River to Lower Granite Dam) versus flow for wild juvenile subyearling fall chinook salmon during 1991 and 1992 indicated that flow alone was a reasonable predictor of travel time (R^2 = 52% to 69%) (Berggren 1994). Predictive power was increased with the inclusion of smoltification-related variables (R^2 = 79%

to 89%). Berggren's regression equation predicted that at a given water temperature or photo period (increasing smoltification as the season progressed was associated with day length), fish greater than 85 mm migrated twice as fast at a flow of 50 kcfs than at a flow of 25 kcfs. In the mid-Columbia, Giorgi et al. (1997) found that summer-migrating ocean-type chinook salmon did not respond to increased flow. However, they did find a positive relationship between migration rate and fish length.

Relating travel time of actively migrating subyearling fall chinook salmon to environmental variables through reservoir reaches has proven difficult for researchers and has produced conflicting results (Berggren and Filardo 1993, Giorgi et al. 1994). Giorgi et al. (1997) found significant correlations between migration rate and flow, water temperature, date, and fish length (although low R^2 resulted in poor predictive capability for all except fish length) for PIT-tagged subyearling chinook salmon in the mid-Columbia River. Fish in this analysis were substantially smaller than migrant Snake River subyearling chinook salmon.

Vendetti et al. (2000) found that migration rates of Snake River fall chinook salmon in the Little Goose Reservoir mirrored reservoir water velocities: both slowed as they approached the dam. Of the variables they examined that might explain the travel time observations, only water velocity consistently changed with travel time.

Connor et al. (1998) found significant correlations between seasonal juvenile fall chinook salmon detection rates at Lower Granite Dam (roughly equivalent to minimum survival estimates) and both average seasonal flow (R^2 = 0.99) and average seasonal water temperature (R^2 = 0.98). Connor et al. (1998) concluded that flow management that provides both flow augmentation and water temperature reduction is a beneficial interim recovery measure for enhancing survival of subyearling chinook salmon in the Snake River.

Study design for PIT-tag analysis

The NMFS has conducted analyses of survival and travel time data from PIT-tagged subyearling fall chinook salmon (Muir et al. 1999, unpublished NMFS analyses reported here). Fish reared at Lyons Ferry Hatchery (Snake RKm 95) were released at Asotin, Billy Creek, and Pittsburg Landing on the Snake River and Big Canyon Creek on the Clearwater River each week from late May to early July from 1995 through 1998. The number of groups and fish per group (Table 8) were large enough to draw conclusions about travel time and survival from release to Lower Granite Dam. For groups released above Lower Granite Dam, indices of exposure to environmental factors were defined as the average daily value measured at Lower Granite Dam between the date of release and the date the 5th percentile passed Lower Granite Dam (see Muir et al. 1999). Environmental factors were flow, temperature, and turbidity. Very few release groups migrated while spill was occurring (typically, no spill occurs during summer months).

Table 8. Data set used to study relationships of survival and travel time from release in the Snake and Clearwater Rivers to Lower Granite Dam with environmental factors for subyearling fall chinook salmon.

Year	Release dates	Number of groups	Range of release sizes	Total number of PIT-tagged fish
1995	31 May - 05 Jul	9	1,124-3,528	16,501
1996	06 Jun - 10 Jul	14	1,147-6,930	28,156
1997	03 Jun - 08 Jul	20	1,238-6,955	36,375
1998	02 Jun - 07 Jul	19	1,249-7,086	35,643
Total		62	1,124-7,086	116,675

To calculate exposure indices based on the week-long period of the 25th to 75th passage percentile would ignore the preceding 5 weeks of common exposure period between the time of release and the 25th passage percentile at the bottom of the reach.

The 5th passage percentile was chosen to increase contrast among the release groups in the indices of exposure, as the protracted residence time above Lower Granite Dam for subyearling chinook salmon released in the Snake and Clearwater Rivers makes use of the middle 50% exposure index inappropriate for analyses of survival and travel time to Lower Granite Dam. Because of the extended travel times for these groups, there was a great deal of overlap among groups in their migration past Lower Granite Dam. Nearly all fish within a group experienced environmental conditions up to the 5th passage percentile date. Using a higher percentile resulted in less contrast in flow and temperature indices among groups, and was not representative for many fish within a group since many had already died because mortality was relatively high for these releases. For this release, the 5th passage percentile did not occur until 34 days after release, while the 25th, 50th, and 75th percentiles occurred at 37, 41, and 44 days respectively (Fig. 9).

An exposure period that encompasses release date to a given passage percentile makes the most sense in terms of capturing environmental conditions experienced by the majority of fish from the release group. Few if any fish are detected in the 30 days following release, indicating that all the fish still alive are above Lower Granite Dam and are experiencing river conditions during this period. For the analyses presented here, we follow the precedent of Muir et al. 1999 and use the release to 5th passage percentile for the exposure index. Extending this period to the 50th passage percentile would only change the exposure period from 5 to 6 weeks (Fig. 9) and would have little effect on results. This is confirmed by the correlation matrix of exposure indices (calculated for release groups from all years) for several different index periods (Table 9). The high correlations show that choice of end date of the exposure period will have little effect on regression results.

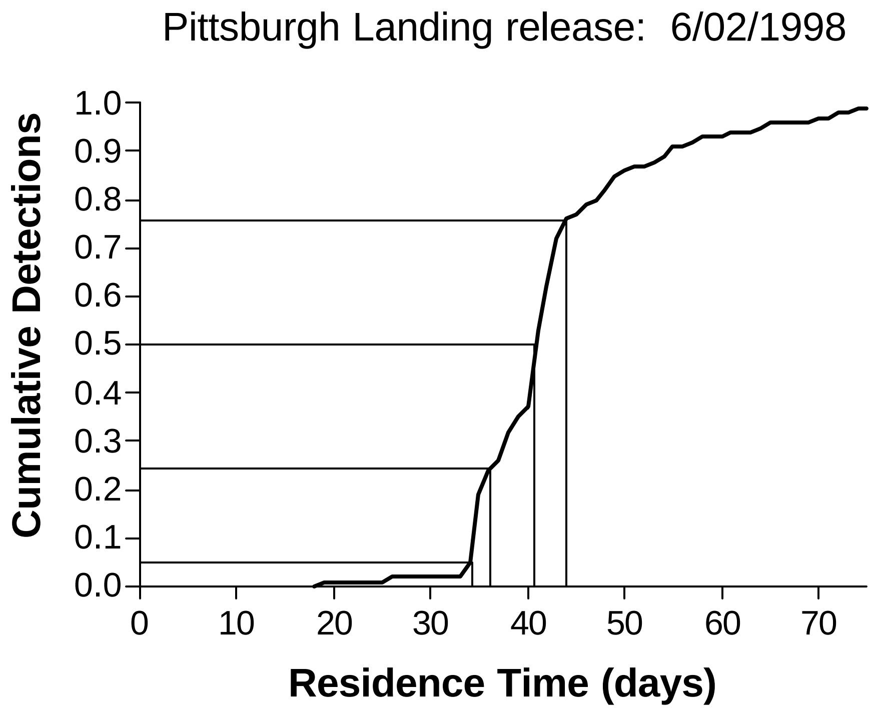


Figure 9. Cumulative detections vs. residence time for a single release of Snake River fall chinook salmon. The lines represent days until the 5th, 25th, 50th, and 75th passage percentiles.

Evaluations of survival and travel time for PIT-tagged subyearling chinook salmon between Lower Granite and Lower Monumental dams were also conducted (Muir et al. 1999, unpublished NMFS analyses detailed here). "Release groups" were constructed by regrouping PIT-tagged subyearling chinook salmon released above Lower Granite Dam according to their date of Lower Granite Dam passage. To construct groups of sufficient size (Table 10), fish detected at Lower Granite Dam were pooled over weekly intervals. Exposure indices for these groups were the averages of the daily values at Lower Granite Dam during the period that fish for that group were detected at Lower Granite Dam.

Table 9. Correlation among exposure indices (measured at Lower Granite Dam) calculated over several different periods for Snake and Clearwater River fall chinook salmon. Percentiles are in terms of cumulative passage. Abbreviation: rel = release date.

Correlation of Flow Indices

	Rel-05%	Rel-10%	Rel-20%	Rel-25%	Rel-50%
Rel-05%	1				
Rel-10%	0.996	1			
Rel-20%	0.987	0.996	1		
Rel-25%	0.984	0.994	0.999	1	
Rel-50%	0.980	0.989	0.995	0.997	1

Correlation of Temperature Indices

	Rel-05%	Rel-10%	Rel-20%	Rel-25%	Rel-50%
Rel-05%	1				
Rel-10%	0.988	1			
Rel-20%	0.975	0.994	1		
Rel-25%	0.973	0.991	0.999	1	
Rel-50%	0.952	0.971	0.980	0.983	1

Correlation of Turbidity Indices

Rel-05%	1				
Rel-10%	0.988	1			
Rel-20%	0.963	0.988	1		
Rel-25%	0.955	0.981	0.998	1	
Rel-50%	0.924	0.952	0.978	0.985	1

Table 10. Data set used to study relationships of survival and travel time from Lower Granite Dam to Lower Monumental Dam with environmental factors for subyearling fall chinook salmon.

Year	Release dates	Number of groups	Range of release sizes	Total number of PIT-tagged fish
Weekly "release" groups from Lower Granite Dam				
1995	11 Jul - 21 Aug	6	105 - 587	1,925
1996	06 Jul - 23 Aug	7	228 - 864	3,266
1997	09 Jun - 01 Sep	13	79 - 3,075	15,426
1998	23 May - 11 Sep	16	45 - 6,276	19,614
Total		42	45 - 6,276	40,231

Release in the Snake and Clearwater Rivers to Lower Granite Dam

In all four years of data (1995-1998), flow generally decreased throughout the period of subyearling chinook salmon migration, and water temperature generally increased (Fig.10). In addition, turbidity decreased (water became clearer) throughout the season. These concomitant trends in environmental factors were accompanied by decreasing survival estimates for later release dates (Fig. 11). Patterns in median travel time were not similar to those for survival and environmental factors (Fig. 11). Typically, groups released around 13-15 June had the shortest travel times, and groups released earlier or later had longer travel times.

Consequently, relationships between indices of exposure to environmental variables and median travel time from release to Lower Granite Dam were not strong or consistent (Table 11, Fig. 12). "Travel time" for subyearling chinook salmon in this stretch of river included several weeks of rearing, during which time the fish grew rapidly and prepared to migrate, and the time taken to travel to Lower Granite Dam once migration was initiated. Thus, as the combination of multiple complex processes, it is not surprising that "travel time" was not a direct response to any of the environmental variables.

The exception was 1997, when median travel time was very strongly correlated with the exposure indices. In that year, median travel time increased as flow decreased, water temperature increased, and turbidity decreased. High flow occurred throughout the entire period of releases in 1997, along with the shortest travel times. The strong correlations with all variables in that year were likely the result of the high flows "flushing" the fish out of their rearing areas. Average fish size was substantially smaller upon arrival at Lower Granite Dam in 1997 than in other years.

The complexity of processes influencing travel time from release to Lower Granite Dam was further illustrated by the stepwise analysis of multi-year data, in which the selected model for all three environmental variables included independent regression lines for each year.

Survival estimates between release and Lower Granite Dam steadily decreased throughout each migration season (Fig. 11), as flow and turbidity generally decreased and water temperatures increased (Fig. 10). The relationships between estimated survival from point of release to Lower Granite Dam tailrace and indices of flow, temperature, and turbidity were strong and fairly consistent across years (Table 12).

The stepwise procedure selected unique effects (slopes) for each year for the relationships between survival and temperature and between survival and turbidity. Nonetheless, the relationships appeared qualitatively similar, slopes nearly parallel for most years (Fig. 13). The unique effects model was significantly, but not highly significantly, better than parallel effects. Unique effects were also chosen for flow exposure (Fig. 13), but this was probably due to the extended range of flow exposures that occurred in 1997. When the analysis was restricted to

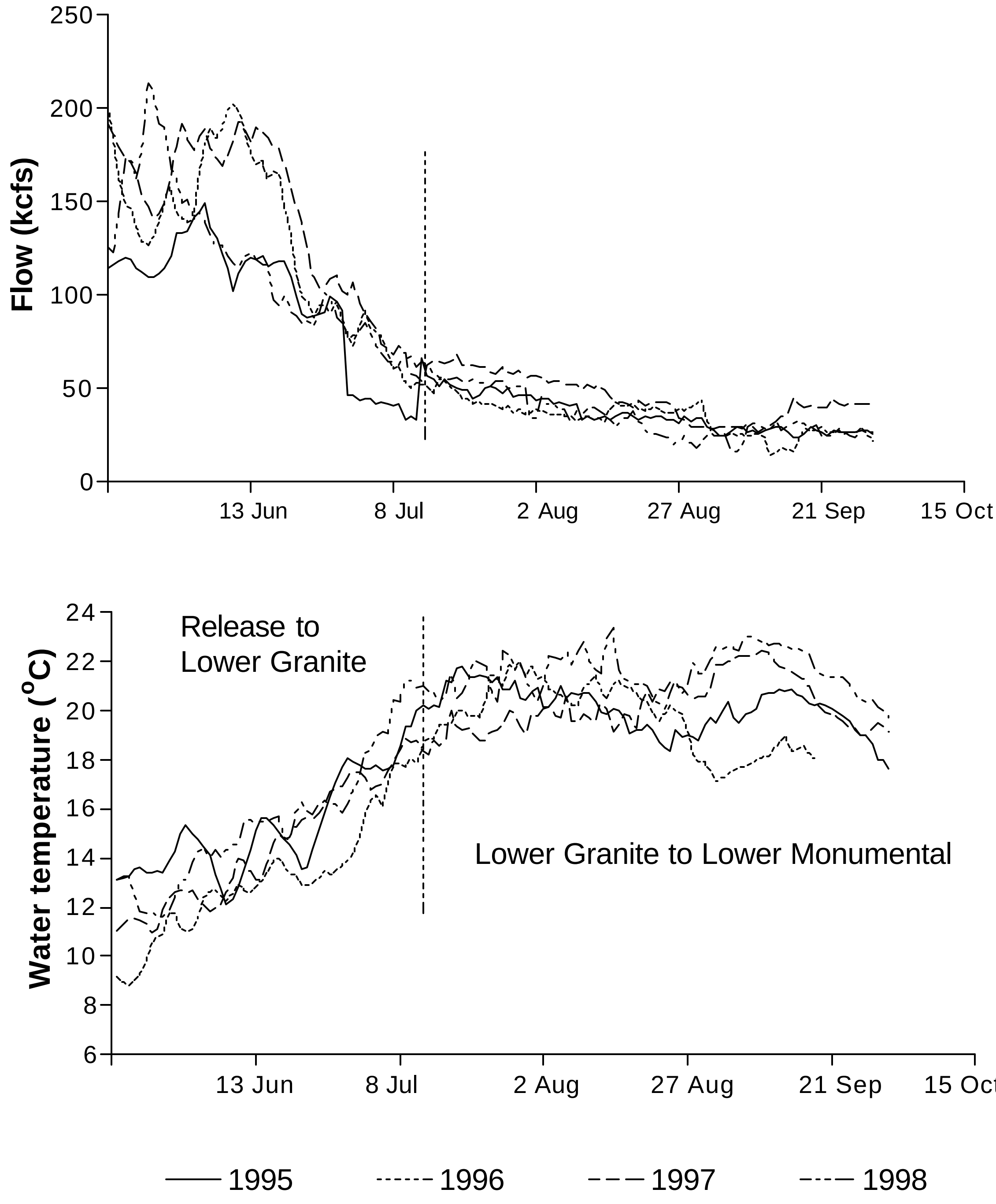
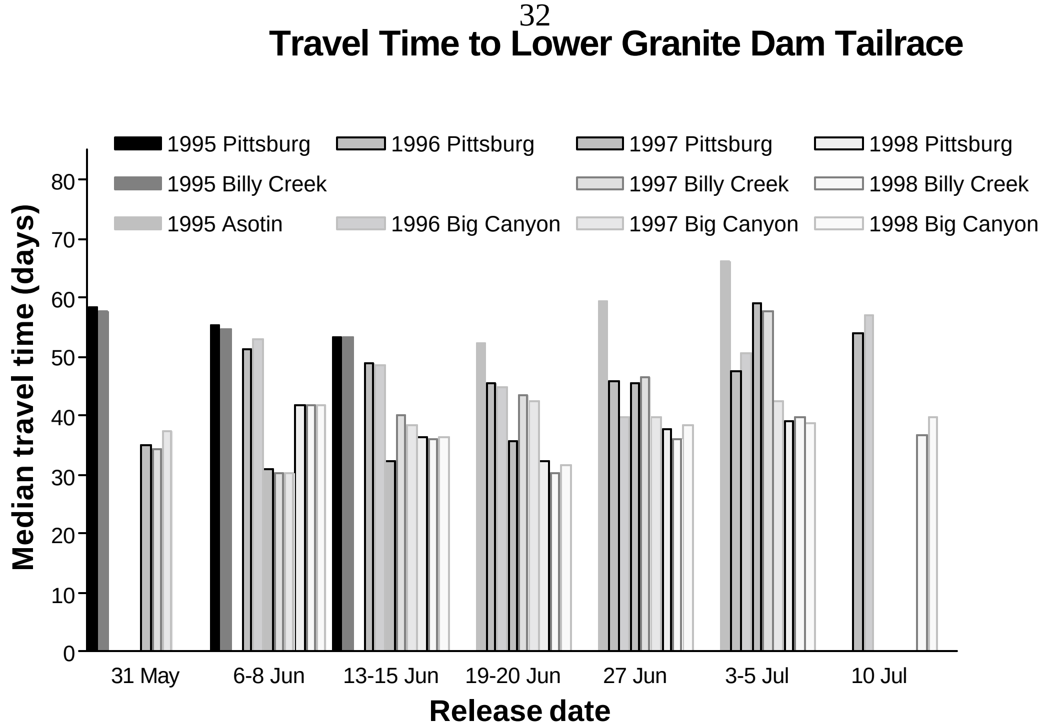


Figure 10. Environmental variables measured at Lower Granite Dam during the subyearling fall chinook salmon migration, 1995-1998. During the time period to the left of the dotted line, most subyearling fall chinook salmon are rearing and migrating to Lower Granite Dam while to the right, most are migrating through the hydropower system.



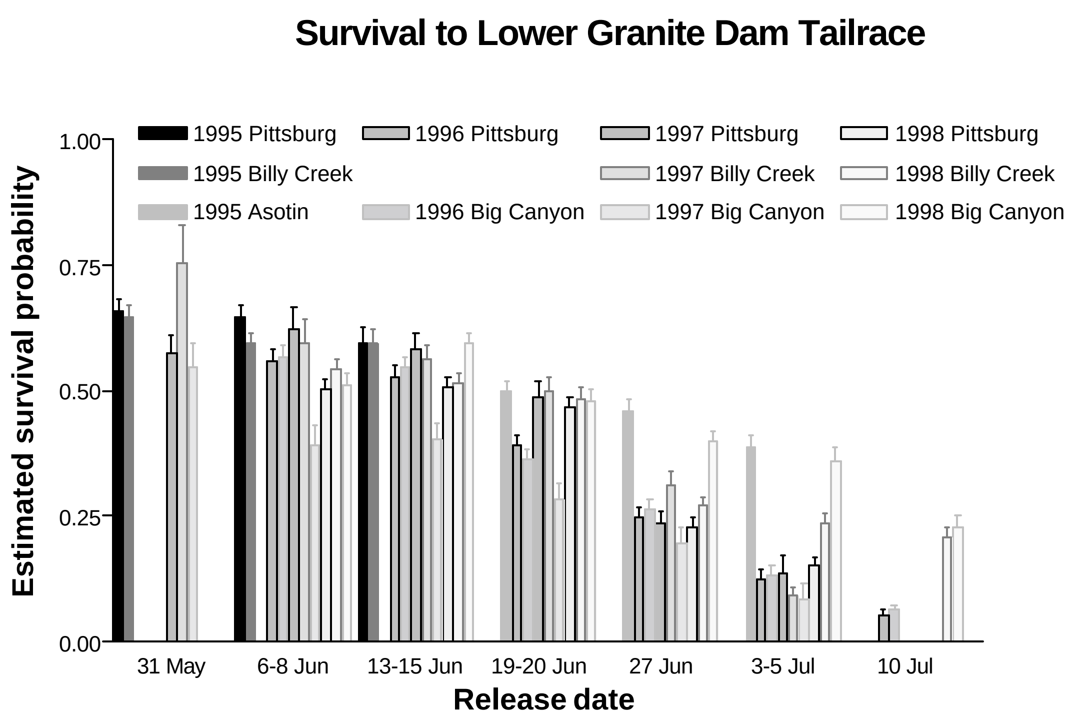


Figure 11. Median travel time and estimated survival (with standard errors) of subyearling chinook salmon from point of release in the Snake (Pittsburg Landing, Billy Creek and Asotin) and Clearwater (Big Canyon Creek) Rivers to the tailrace of Lower Granite Dam, 1995-1998.

Table 11. Summary of linear regression results for median travel time (days from release to Lower Granite Dam) of release groups of subyearling fall chinook salmon in Snake and Clearwater Rivers. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2 (%)	P value	intercept	slope
Flow (full range)	1995	25.3	0.168	67.01	-0.116
(kcfs)	1996	0.4	0.837	47.80	0.010
	1997	59.5	<0.001	55.78	-0.136
	1998	2.3	0.532	34.43	0.035
	all years (**1**)	28.0			
Temperature	1995	31.3	0.118	35.28	1.252
(°C)	1996	1.3	0.697	43.73	0.284
	1997	57.0	<0.001	-9.48	2.999
	1998	0.4	0.806	35.54	0.109
	all years (**1**)	77.5			
Turbidity	1995	16.6	0.276	46.89	2.744
(Secchi disk)	1996	0.4	0.840	47.72	0.257
	1997	68.1	<0.001	23.45	7.943
	1998	0.1	0.890	38.43	-0.317
	all years (**1**)	79.9			
Flow (<120 kcfs)	1995	25.3	0.168	67.01	-0.116
	1996	0.1	0.912	48.89	-0.007
	1997	36.8	0.063	65.93	-0.260
	1998	2.3	0.532	34.43	0.035
	all years (**1**)	75.7			

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

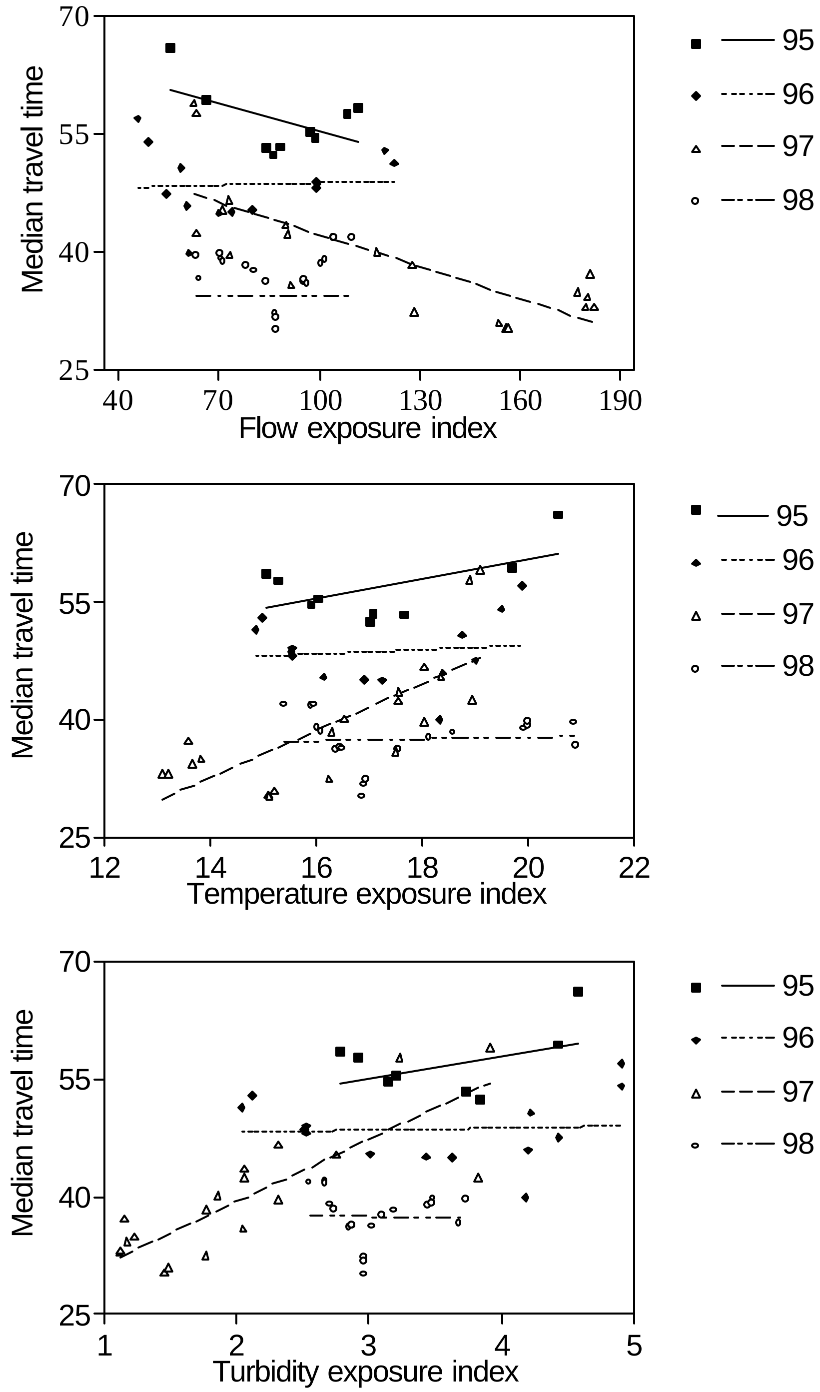


Figure 12. Median travel time of subyearling chinook salmon (days from point of release to Lower Granite Dam) vs. mean daily flow, temperature and turbidity exposure measured at Lower Granite Dam from release to 5 percent passage date at Lower Granite Dam. Data from unpublished NMFS analyses.

Table 12. Summary linear regression results for estimated survival probability (release to Lower Granite Dam) of release groups of subyearling fall chinook salmon in Snake and Clearwater rivers. Data from unpublished NMFS analyses. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2 (%)	P value	intercept	slope
Flow (full range)	1995	86.3	<0.001	0.147	0.005
(kcfs)	1996	81.2	<0.001	-0.200	0.007
	1997	74.3	<0.001	-0.028	0.004
	1998	68.8	<0.001	-0.374	0.009
	all years (**1**)	78.1			
Temperature	1995	83.9	0.001	1.340	-0.045
(°C)	1996	92.2	<0.001	2.247	-0.110
	1997	74.5	<0.001	1.846	-0.087
	1998	68.3	<0.001	1.731	-0.073
	all years (**1**)	80.8			
Turbidity	1995	85.7	<0.001	1.058	-0.137
(Secchi disk)	1996	89.6	<0.001	1.009	-0.189
	1997	78.8	<0.001	0.867	-0.216
	1998	65.4	<0.001	1.560	-0.369
	all years (**1**)	81.2			
Median travel time	1995	30.9	0.120	1.260	-0.012
(Days)	1996	4.8	0.453	0.843	-0.010
	1997	58.8	<0.001	1.197	-0.019
	1998	0.3	0.838	0.528	-0.002
	all years (**2**)	33.2			-0.0158
Flow (<120 kcfs)	1995	86.3	<0.001	0.147	0.005
	1996	82.9	<0.001	-0.252	0.008
	1997	81.5	<0.001	-0.421	0.009
	1998	68.8	<0.001	-0.374	0.009
	all years (**2**)	81.1			0.0079

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

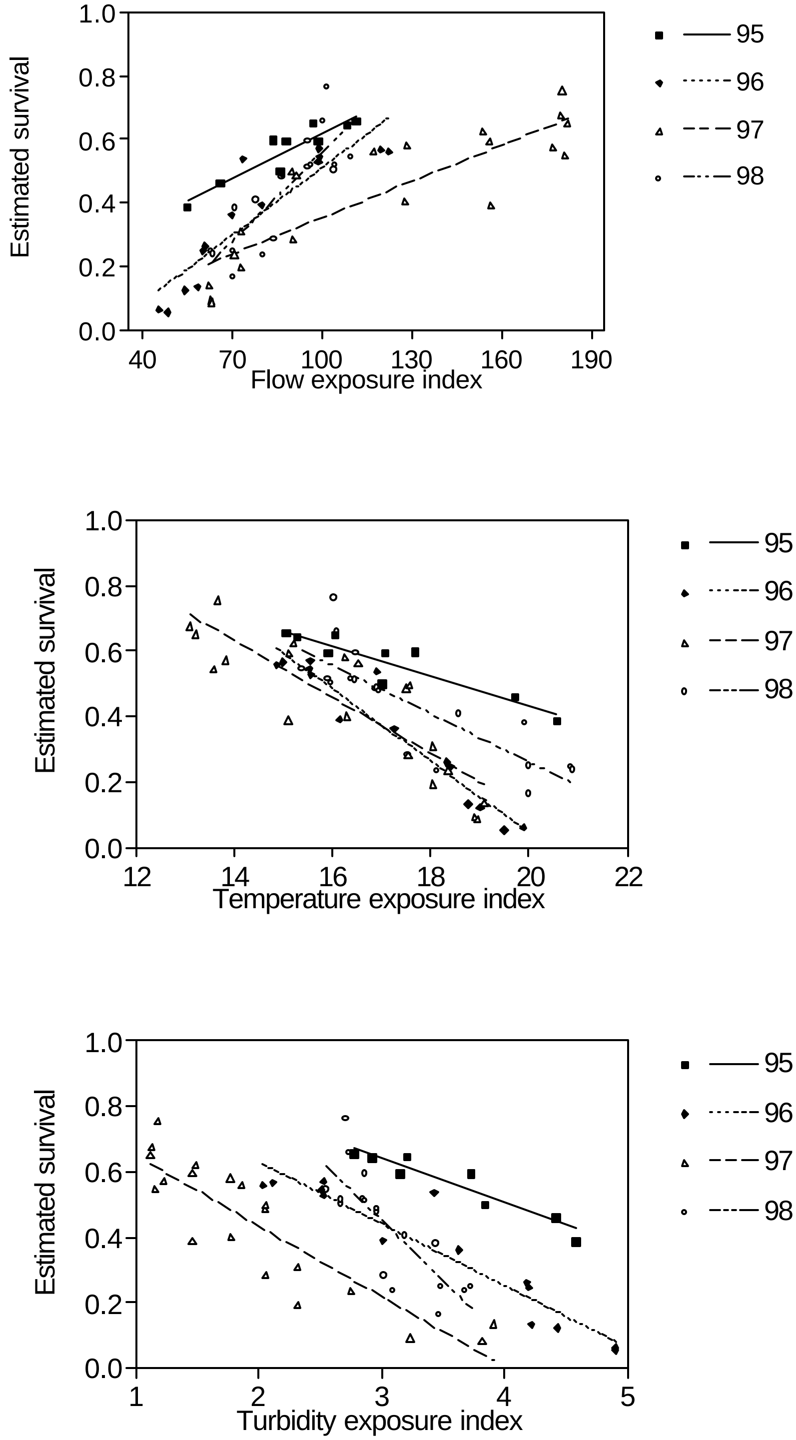
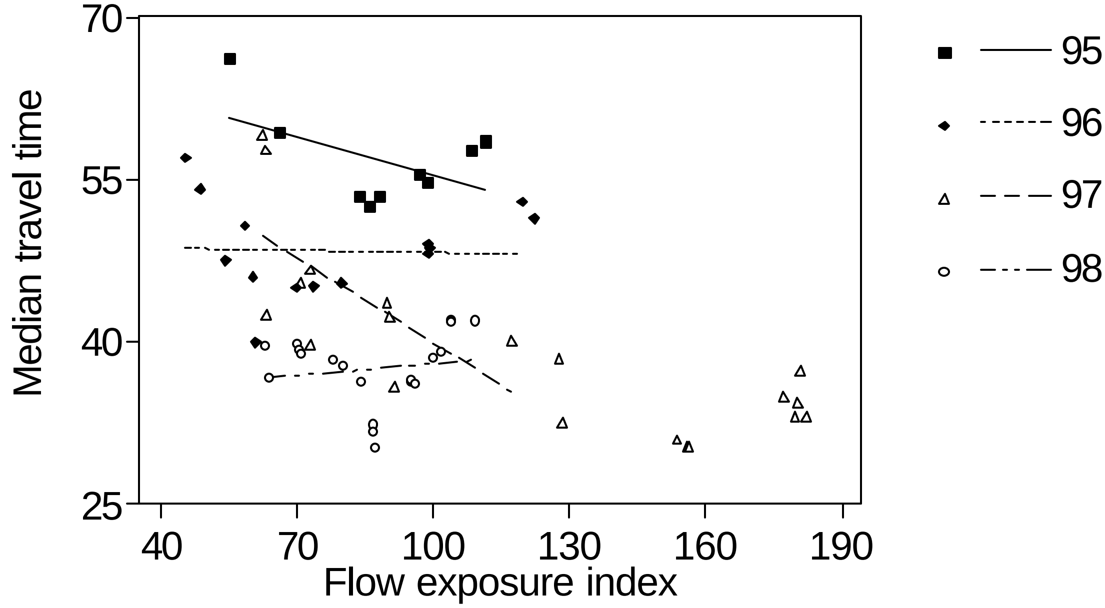


Figure 13. Estimated survival of subyearling chinook salmon from point of release to Lower Granite Dam vs. mean daily flow, temperature and turbidity exposure measured at Lower Granite Dam from release to 5 percent passage date at Lower Granite Dam. Data from unpublished NMFS analyses.



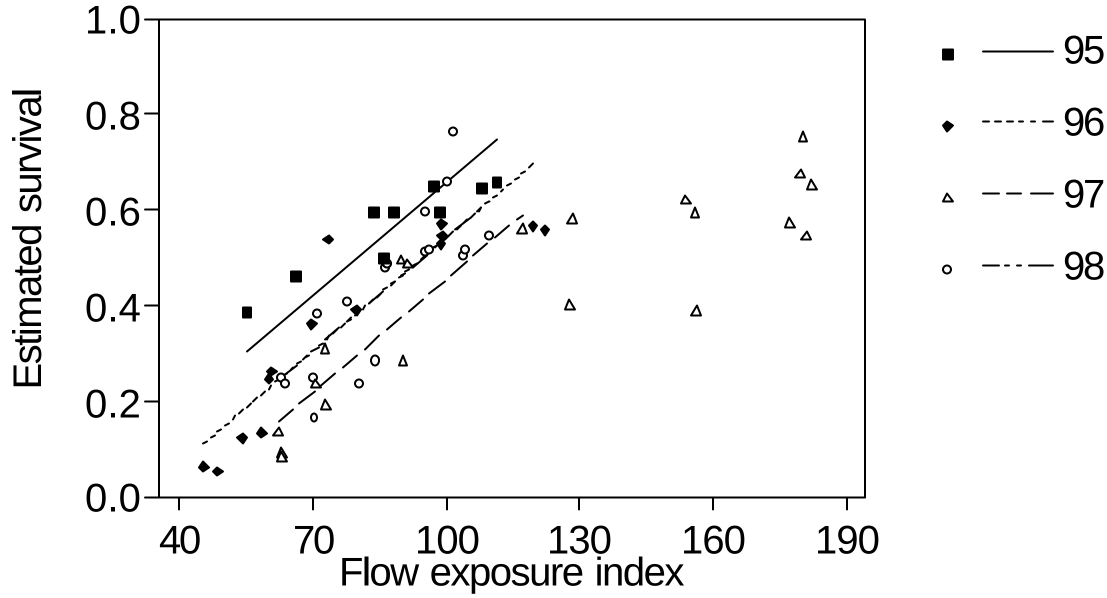


Figure 14. Median travel time and estimated survival of subyearling chinook salmon from point of release to Lower Granite Dam vs. mean daily flow measured at Lower Granite Dam from release to 5 percent passage date at Lower Granite Dam. Analysis restricted to release groups with flow index less than 120 kcfs. Data from unpublished NMFS analyses.

release groups that had flow indices less than 120 kcfs (i.e., the portion of the overall range shared by all years), the parallel-response model was chosen for flow (Fig. 14). Over the entire range of flow exposures in 1997, the relationship between flow and survival appeared to curve, with a shallower slope at higher than at lower flows (Figs. 13 and 14). The travel time relationships required unique regression lines even over the restricted range of flow exposures (Fig. 14).

Lower Granite Dam to Lower Monumental Dam

In single-year regression analyses for the Lower Granite Dam to Lower Monumental Dam reach, all but one combination of exposure index and response variable have produced both positive and negative correlations within single years, and the strength of the correlations has been highly variable (Tables 13 and 14). The exception is that negative correlation was consistently observed between median travel time and the Secchi disk reading (clearer water associated with longer travel times).

Of the four years of study, the lowest survival estimates and longest travel times between Lower Granite and Lower Monumental dams were observed in 1997, which was unexpected due to the high flows in that year. A possible cause of this anomaly is that high flows in June and early July prematurely flushed subyearling chinook salmon from their rearing areas in free-flowing river stretches, and the fish continued to rear extensively after they passed Lower Granite Dam. Moreover, the longest travel times in 1997 were observed for the earliest groups passing Lower Granite Dam, despite higher flows. The 1997 data strongly influences the stepwise procedure’s selection of the parallel-lines model for median travel time versus flow exposure, with the parallel lines having positive slope, indicating longer travel times at higher flows. (Using a significance level of 0.05 in the stepwise approach, instead of 0.10, resulted in selection of a model with differing annual average travel time, and no relationship with flow exposure).

Higher flows in 1997 also increased the amount of debris at the Snake River dams, resulting in blockages within the bypass systems. In particular, blockages in the PIT-tag portions of the bypass systems required additional dewatering. Delayed mortality was higher for natural subyearling fall chinook salmon at Little Goose Dam during 1997 (7.7%) compared to 1995 (2.2%) and 1996 (1.4%), and higher than normal levels of columnaris infections were observed (Rex Baxter, COE, pers. commun., July 1999).

Despite the variability in single-year regression results for travel time from Lower Granite Dam to Lower Monumental Dam (Table 13), the stepwise procedure selected the parallel-effects model for the relationship between median travel time and all three environmental factors (Fig. 15). The primary cause of variability in single-year results is narrow ranges of exposures in 1995 and 1996. Years with wider ranges of exposure (1997 and 1998) give more information on the relationships, and consequently have more influence on the results of the multi-year stepwise procedure.

Table 13. Summary of linear regression results for median travel time (days from Lower Granite Dam to Lower Monumental Dam) of weekly release groups of subyearling fall chinook salmon from Lower Granite Dam. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2 (%)	P value	intercept	slope
Flow (kcfs)	1995	73.7	0.029	21.61	-0.231
	1996	24.5	0.258	-3.90	0.357
	1997	45.4	0.012	7.36	0.159
	1998	3.8	0.472	10.29	0.028
	all years (**2**)	35.0			0.0775
Temperature (°C)	1995	33.1	0.232	52.39	-1.826
	1996	18.5	0.336	-33.25	2.042
	1997	57.5	0.003	76.43	-3.043
	1998	27.8	0.036	30.80	-0.943
	all years (**2**)	48.6			-1.157
Turbidity (Secchi disk)	1995	- - - - - unavailable - - - - -			
	1996	84.3	0.004	20.75	-3.701
	1997	53.1	0.005	30.41	-5.892
	1998	28.8	0.032	27.18	-5.050
	all years (**2**)	56.0			-5.114

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

Table 14. Summary of linear regression results for estimated survival probability (Lower Granite Dam to Lower Monumental Dam) of weekly release groups of subyearling fall chinook salmon from Lower Granite Dam. For all years combined, the model selected is provided in the parentheses along with appropriate regression information.

		Linear regression			
Exposure Index	Year	R^2 (%)	P value	intercept	slope
Flow (kcfs)	1995	54.4	0.094	0.089	0.015
	1996	11.5	0.457	1.715	-0.027
	1997	52.0	0.005	-0.013	0.007
	1998	32.4	0.021	0.347	0.005
	all years (**2**)	48.0			0.0053
Temperature (°C)	1995	35.8	0.210	-2.379	0.139
	1996	29.0	0.212	-5.397	0.284
	1997	76.9	0.000	3.342	-0.149
	1998	8.6	0.271	1.230	-0.030
	all years (**1**)	46.5			
Turbidity (Secchi disk)	1995	- - - - - unavailable - - - - -			
	1996	22.9	0.278	1.252	-0.214
	1997	32.3	0.043	0.858	-0.195
	1998	11.4	0.201	0.073	0.183
	all years (**3**)				
Median travel time (Days)	1995	51.8	0.107	1.322	-0.053
	1996	2.8	0.722	0.456	0.018
	1997	51.8	0.006	-0.107	0.031
	1998	3.7	0.478	0.757	-0.011
	all years (**3**)				

Model numbers for all years combined:
1 = unique effects (slope varies by year; slope provided for each year)
2 = parallel effects with response (common slope given for all years model)
3 = parallel effects no response (zero slope)
4 = common effects with response (common slope, intercept given for all years model)
5 = common effects no response (zero slope)

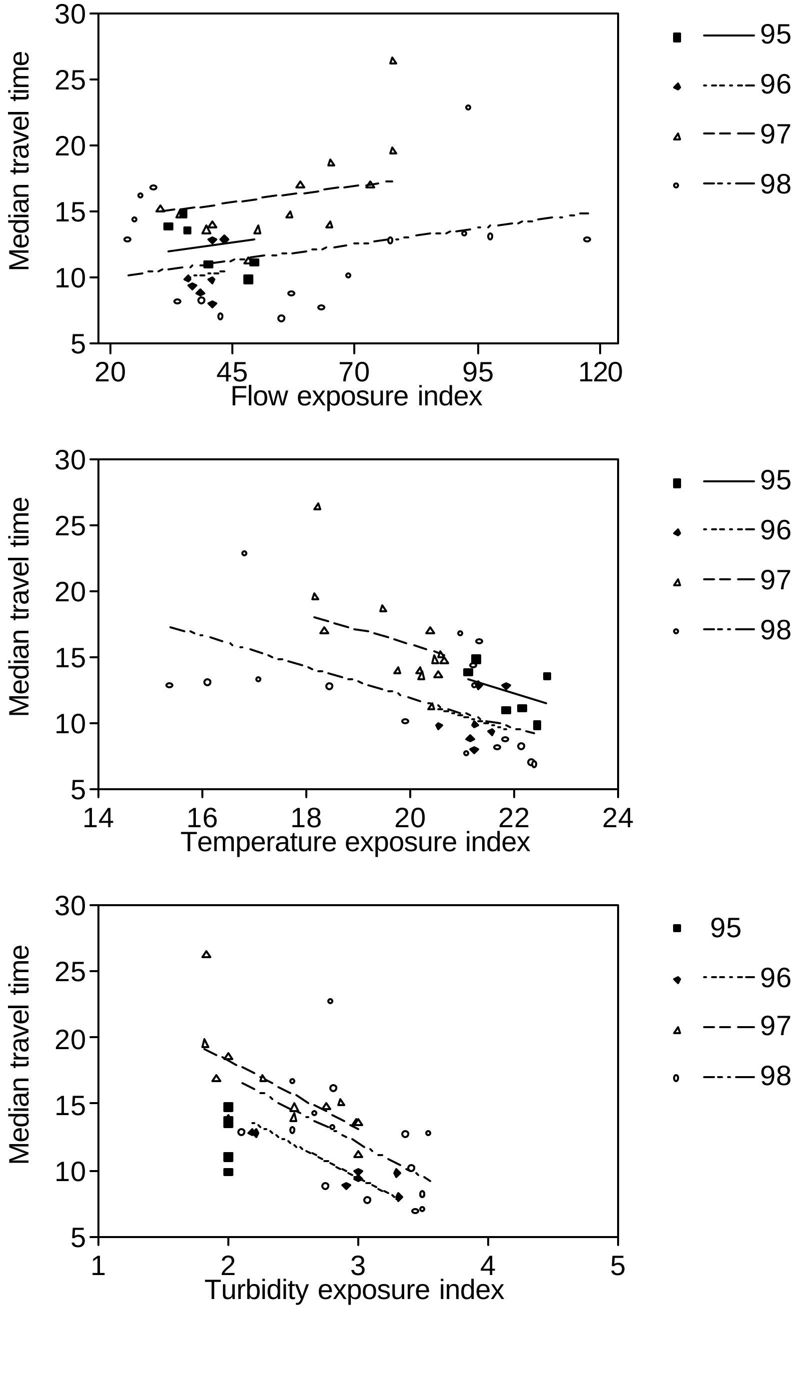


Figure 15. Median travel time (days from Lower Granite Dam to Lower Monumental Dam) of subyearling chinook salmon vs. mean daily flow, temperature and turbidity exposure measured at Lower Monumental Dam between dates of 25 and 75 percent passage date at Lower Monumental Dam. Data from unpublished NMFS analyses.

The stepwise procedure also selected the parallel-effects model for the relationship between flow and survival from Lower Granite Dam to Lower Monumental Dam (Fig. 16), again being less influenced by the narrow range of flows in 1996 than by wider rages in other years. As with the flow-survival relationship above Lower Granite Dam, results for the year with the widest range of flow exposure (1998) strongly suggested that the relationship is curved. There appeared to be a maximum level of flow above which no survival increase was observed. Results for survival and temperature are more difficult to interpret (Fig. 16). The years with wider range of exposure (1997 and 1998) had varying negative slopes (higher temperature related with lower survival), while the years with narrow ranges (1995 and 1996) had steep positive (and biologically nonsensical) slopes. No relationship was observed between turbidity and survival from Lower Granite Dam to Lower Monumental Dam (Fig. 16).

Conclusions for fall chinook salmon

Estimated survival probability from release points in the Snake River Basin to the tailrace of Lower Granite Dam was significantly correlated with flow, water temperature, and turbidity. Also, survival decreased markedly from early to late release dates. Because the environmental variables were highly correlated with each other, determining which variable was most important to subyearling fall chinook salmon survival is not possible.

River flow, water temperature, and turbidity may affect survival for subyearling fall chinook salmon in a number of ways. Fish that migrate under lower flows later in the season may experience passage delays that do not occur early in the season. Hypothesized causes for such delays are disorientation of migrants, reversal of smoltification, disease (Park 1969, Raymond 1988, Berggren and Filardo 1993) and a decreased tendency to migrate under conditions of low turbidity (Steel 1999). In addition, operations at dams are changed under lower flows (e.g., less spill, greater diel-flow fluctuations) that can decrease fish survival. Warmer water for late season migrants leads to increased predation rates due to increased metabolic demands of predators (Curet 1993, Vigg and Burley 1991, Vigg et al. 1991). Fish guidance efficiency of turbine intake screens is also reduced in warmer water, resulting in more fish passing through turbines (Krcma et al. 1985), which may cause decreased survival. Vulnerability to sight-feeding predators may also increase as turbidity decreases (Zaret 1979) by increasing predator reactive distance and encounter rates (Vinyard and O'Brien 1976, Shively et al. 1991). Higher turbidity could reduce predation rates on juvenile salmonids by providing protective cover during rearing (Simenstad et al. 1982, Gregory 1993, Gregory and Levings 1998).

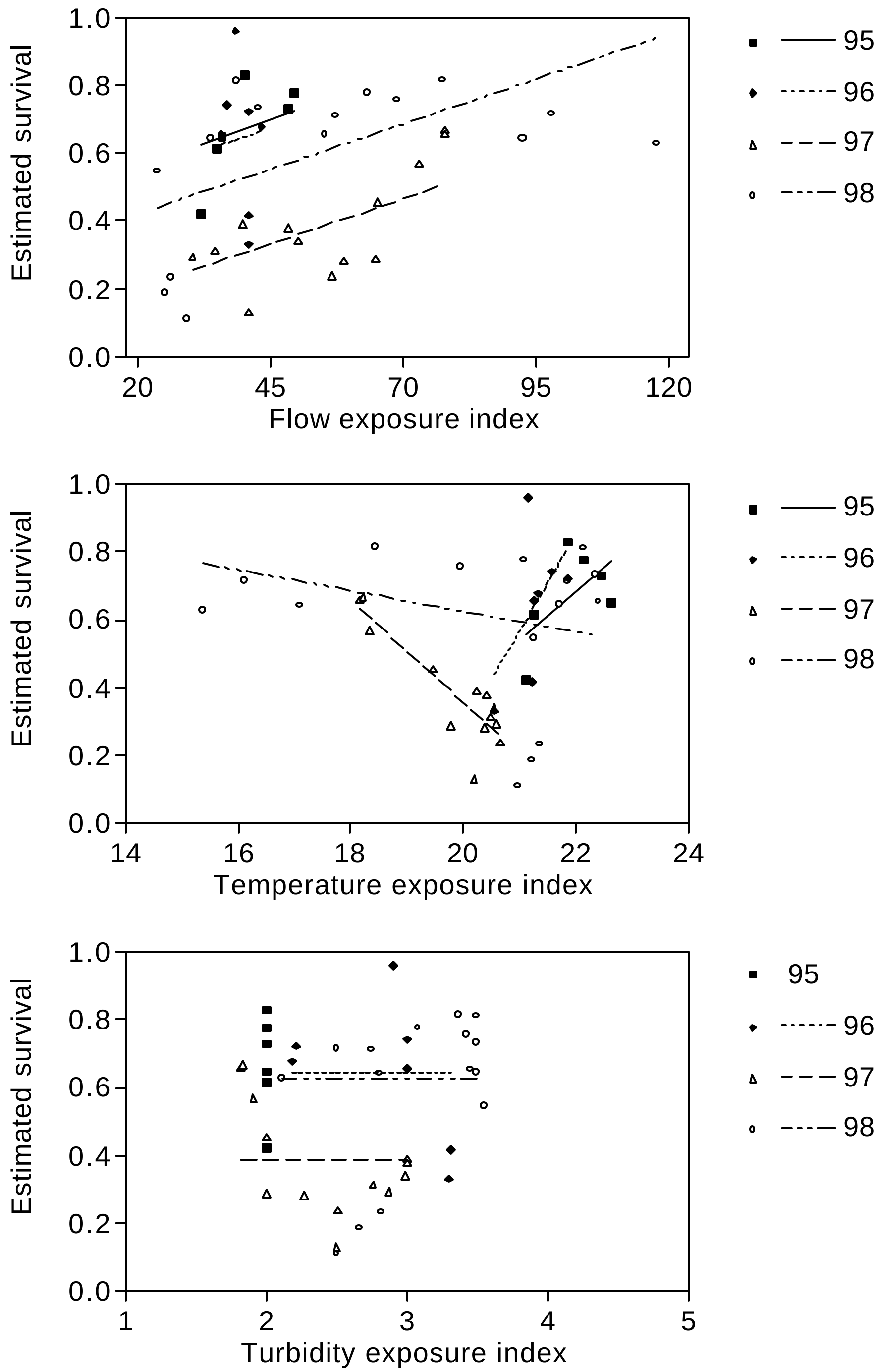


Figure16. Estimated survival probability (Lower Granite Dam to Lower Monumental Dam) of subyearling chinook salmon vs. mean daily flow, temperature and turbidity exposure measured at Lower Monumental Dam between dates of 25 and 75 percent passage date at Lower Monumental Dam. Data from unpublished NMFS analyses.

Predator abundance and feeding selectivity, in concert with decreasing flow and increasing water temperature, may have caused the steady decline in survival probability estimates throughout the migration season. Isaak and Bjornn (1996) found that peak abundance of northern pike minnow (*Ptychocheilus oregonensis*) in the tailrace of Lower Granite Dam occurred in July. Poe et al. (1991) and Shively et al. (1996) found that predation rates depended on the size of juvenile salmonids, with smaller fish more vulnerable to predation. Fish size is one of the variables known to affect migration rates in fall chinook salmon, with smaller fish rearing longer in upstream areas before initiating migration (Connor et al. 1994). Thus, small subyearling fall chinook salmon that migrate late in the year likely experience higher predation rates and lower survival as was reported for natural subyearling chinook salmon in the Clearwater River (Connor et al. 1997a,b). However, the low survival estimate (17% in 1995) may have resulted from unseasonably cold water releases from Dworshak Dam during the Clearwater River wild fall chinook salmon rearing period. Thus, summer flow augmentation to cool the Snake River in July and August may have adverse affects on wild fall chinook salmon growth and may delay or inhibit subyearling smolt development in the Clearwater River (Arnsberg and Statler 1995). Fisheries managers recognize this potential and delay releasing cool water from Dworshak Reservoir until the Clearwater subyearling chinook salmon reach an average size of 85 mm.

Interpretation of Results from Juvenile Studies

Identifying and quantifying relationships between environmental variables and travel times or survival of PIT-tagged migrant juvenile salmonid release groups in the Snake River present difficult challenges. Among these is defining the environmental conditions to which a release group is exposed. While operations to produce power have decreased the long-term flow variability inherent in the natural river flows of the Columbia and Snake Rivers, flows often vary widely over short times as generation is varied to match the electrical load demand. This occurs during both spring and summer. However, the percentage of change is likely higher during the summer when the base flow is much lower. For example, it is not uncommon for summer flows to vary as much as ± 40% (e.g., 11.5 ± 4.5 kcfs) on a daily basis downstream from Hell's Canyon Dam. More sustained decreases in discharge also frequently occur over weekends as electrical demand declines. Because environmental conditions change over a short time relative to the time it takes for the bulk of a release group to migrate through a particular river section, the group is exposed to a range of environmental conditions. Further, fish from a single release group do not migrate as a group, but spread out over time. The problem is not too severe for yearling migrants. For example, in the spring, the average difference in travel time between the 10^{th} and 90^{th} percentiles for fish that passed between the tailrace of Lower Granite and McNary Dam was approximately 7 days. However, for example, fall chinook salmon juveniles released into the Snake River at Billy Creek, just upstream from Lower Granite Reservoir, on 10 June 1997 were detected at Lower Granite Dam a median of 30 days later. However, individual fish were detected as early as 10 days and as late as 112 days after release (Muir et al. 1999). In this situation, estimated survival probabilities (determined post-season after all released fish have passed, died, or residualized) are valid estimates of average survival for the group; however, it is impossible to uniquely characterize the environmental conditions to which the entire release group was exposed.

There are also important biological differences between study groups. Significant relationships have been detected between release date and travel time for yearling and subyearling chinook salmon and steelhead and have been hypothesized to relate strongly to the degree of smoltification (Berggren and Filardo 1993, Zabel et al. 1998). Muir et al. (1994) demonstrated that smolt development and travel time of hatchery yearling chinook salmon could be altered by artificially advancing photo period and increasing water temperature prior to release. For yearling chinook salmon, the date of entry into a mid-Columbia index reach was strongly correlated with travel time, and was assumed related to higher flows and increased smoltification (Berggren and Filardo 1993). For subyearling chinook salmon, fish identified with longer travel times later in the season may have had lower levels of smoltification (Berggren and Filardo 1993).

Smolt-to-adult Returns and Spawner/recruit Data

Two common measures of stock performance are smolt-to-adult (SAR) returns and recruits per spawner (R/S). SARs are measured at a specific point on the migration route, for example at a dam where both smolts and adults are observed, and are calculated as the proportion (or percentage) of returning adults from a population of smolts. They are a measure of survival through downstream migration, estuary/ocean residence, and upstream migration. If harvest of adults occurred, harvested fish are added to the adult numbers. Recruits per spawner is a measure of the number of recruits returning from a brood year of spawners. Spawner numbers are estimated from spawning ground data (usually redd counts), and recruits are measured either to the spawning ground or some point previous to that on the migratory route (e.g., recruits to Bonneville Dam). Thus R/S incorporates more components of the salmon life history (in particular egg-to-smolt survival) than does SAR. One commonly adopted measure of survival is natural log recruits per spawner (ln(R/S)).

In this section, several studies that have compared SARs or ln(R/S) with flow conditions are reviewed. When data were accessible, the analyses were extended to incorporate the most recent data. Also, since this paper addresses the issue of flow augmentation under current conditions, data points were removed from years before the hydropower system was completed (before 1969 for the upper Columbia River and before 1975 for the Snake River) because: 1) with fewer dams, water travel time is shorter due to fewer impoundments; 2) dams impart direct mortality and there is no way of separating direct effects of dams from effects of water travel time; and 3) as SARs were measured from the uppermost dam, previous to 1975, the migratory route was a shorter distance.

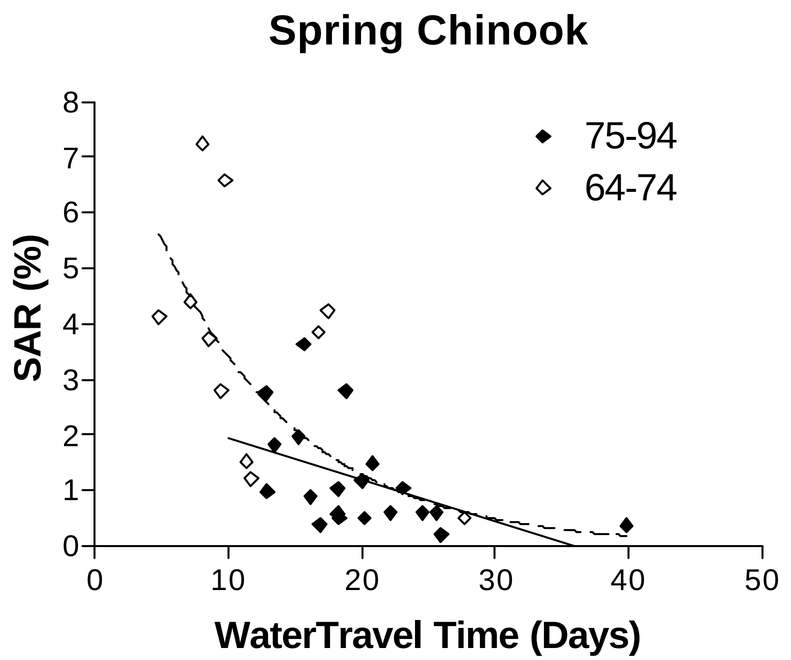
<u>Snake River wild steelhead and spring/summer chinook salmon</u>

Petrosky (1992) evaluated SARs from the upper Snake River dam until their return to that dam. He found a significant relationship between Raymond's (1988) 1964-1984 aggregate wild Snake River spring/summer chinook salmon and steelhead SARs compared to water particle travel time between Lewiston, Idaho, and Ice Harbor Dam ($R^2 = 0.66$, $P < 0.001$ and $R^2 = 0.48$, $P < 0.001$, respectively). Petrosky and Schaller (1998) updated the Snake River spring/summer chinook salmon SAR estimates to include the 1985-1994 migration years and adjusted the 1964-1984 estimates to remove harvest mortality, and Marmorek et al. 1998 found a strong relationship between water particle travel time in the Snake River and SAR (chinook salmon R^2 = 0.54; steelhead R^2 = 0.36) (Fig. 17). The strong fit of the exponential curve to these data implies an increasing benefit of decreasing water travel time.

Also, additional years (1985-1991) of spring chinook salmon SARs were calculated and incorporated in the analysis. We re-analyzed these data for only the years after Lower Granite was in place (migration years 1975-1994). Following Petrosky (1992) and Marmorek et al. (1998), an exponential curve ($SAR = a \cdot \exp(-b \cdot WTT)$ with *WTT* = water travel time in days) was fit to this later time series and to the entire time series. The results are presented in Fig. 17 and Table 15. For the chinook salmon over the period 1975-1994, the fitting algorithm did not converge with the exponential equation. This is likely because of the lack of data below 12 days water travel time could not define the steep portion of the curve. For these data a linear equation ($SAR = a + b \cdot WTT$) was fit and the result are presented in Table 15 and Fig. 17.

For both spring chinook salmon and steelhead, the relationship between SAR and water travel time is weaker over the period 1975-1994 as compared to the entire time series (Fig. 17). For spring chinook salmon during the later time period, the slope is still significantly different than zero (95 % confidence interval does not contain zero, Table 15). For steelhead, though, the slope parameter (i.e., the decay parameter b in the exponential equation) is not significantly different from zero during the later time period. A linear regression for steelhead gives similar results. While the year 1977 is influential for both spring chinook salmon and steelhead, omitting it from the analysis does not change the results substantially.

One major difference resulting from the range of years analyzed here as compared to those analyzed by Petrosky (1992) and Marmorek et al. (1998) is that shorter water travel times (and corresponding higher SARs) were not represented, and these years drove the previously published relationships. However, because the earlier years had fewer impoundments, it is likely not possible to attain the water travel times observed in those years in the current hydropower system configuration.



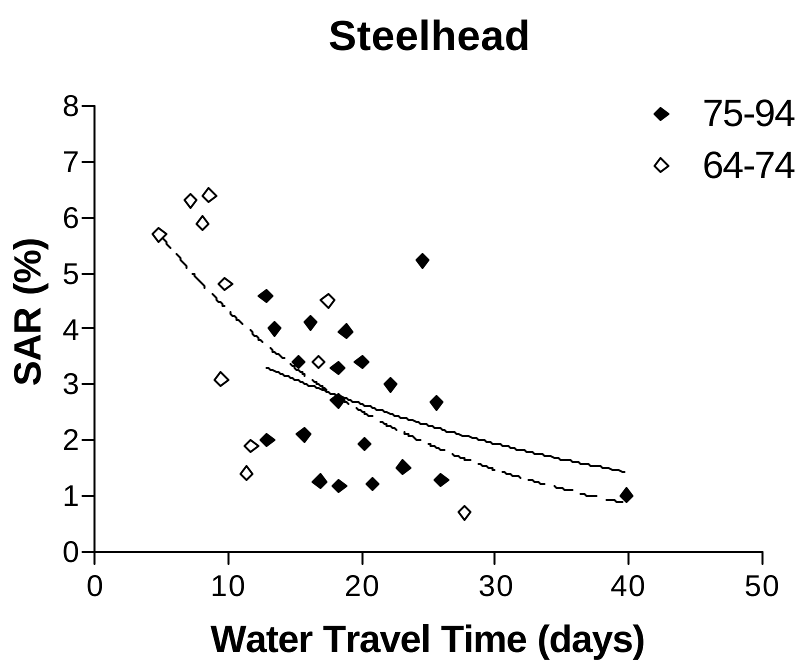


Figure 17. Regressions of smolt-to-adult returns versus water travel time for Snake River wild steelhead and spring/summer chinook salmon for the 1964-1994 smolt migration (after Petrosky and Schaller 1998). The dashed line represents the regression line for the entire period; the solid line is for the years 1975-1994.

Table 15. Regression results for SAR versus water travel time for Snake River wild steelhead and spring/summer chinook salmon. Regressions were performed over the entire time period (1964-1994), early period (1964-1974), and late period (1975-1994). An exponential curve ($SAR = a \cdot \exp(-b \cdot WTT)$ with *WTT* = water travel time in days) was fit to the data in all cases except for the late period spring/summer chinook salmon; for these data a linear equation ($SAR = a + b \cdot WTT$) was fit.

Period	N	a	(95 % CI)	b	(95 % CI)	R^2
Spring/summer chinook salmon						
1964-1994	31	9.00	(4.51, 13.49)	0.097	(0.054, 0.140)	0.496
1964-1974	11	6.47	(0.70, 12.24)	0.050	(-0.036, 0.136)	0.244
1975-1994[a]	20	*2.70*	*(1.31, 4.08)*	*-0.075*	*(-0.142, -0.008)*	*0.238*
Steelhead						
1964-1994	31	7.42	(4.69, 10.16)	0.054	(0.028, 0.080)	0.400
1964-1974	11	8.86	(2.72, 15.00)	0.072	(0.000, 0.145)	0.480
1975-1994	20	4.94	(0.64, 9.24)	0.031	(-0.015, 0.077)	0.129

[a] For this time period, a linear regression was performed because the nonlinear fit did not converge.

Petrosky (1991) also estimated the R/S ratios based on redd counts for Marsh Creek and Big Creek (tributaries to the Middle Fork Salmon River) spring/summer chinook salmon recruits for brood years 1975-1985 (migration years 1977-1987). Because recruitment of salmonids is likely influenced by the number of spawners, both spawner-to-recruit survival and number of spawners were regressed against mean seasonal Snake River flow during the smolt migration season. In the resulting multiple regression, a significant ($P < 0.001$) positive coefficient was associated with flow. In the final model, which included both flow and spawner abundance, flow explained a large proportion of the variability ($R^2 = 0.78$ to 0.82, depending upon method of averaging flow). We note, however, that by combining the Marsh Creek and Big Creek spawner/recruit data into one multiple regression, assumptions of independence were violated, and the resulting P-values were much lower than if the stocks had been treated separately or averaged.

Following the methods of Petrosky (1991), we analyzed the relationship between Marsh Creek ln(R/S) and mean river flow in the Snake River during the peak migration season. Instead of using data from Petrosky (1991), we used the Marsh Creek spawner and recruit data available from Streamnet (www.streamnet.org). These data were used because more years are available, they are readily obtainable, and they are the data used both by PATH (Marmorek et al. 1998) and the NMFS CRI analysis (CRI 2000). We extended the Petrosky time series to brood year 1990 (migration year 1992) and also included the brood years 1973 and 1974. For years not analyzed by Petrosky, river flows at Lower Granite were obtained from the UW Dart web site (www.cqs.washington.edu). Table 16 and Fig. 18 present an analysis with flows from the "peak" migration period (April 15-May 5). Petrosky (1991) also analyzed flows from the "extended" migration period (April 20-May 30); we conducted a similar analysis, and the results were similar to those obtained from the "peak" flow analysis.

Over the extended period (brood years 1973-1990), a significant positive relationship ($P = 0.014$; $R^2 = 0.323$) existed between natural log recruits per spawner and mean river flow in the Snake River during the peak migration period. Adding spawners to this relationship only improved the fit slightly ($R^2 = 0.382$), and the spawner parameter was not significant ($P = .253$).

For comparison purposes, we conducted the analysis over the same period as Petrosky (1991). The results are contained in Table 16. While we obtained a similar fit as Petrosky (1991) for the model containing both flow and spawners ($R^2 = .808$), the flow parameter was (barely) not significant under this model ($P = 0.051$). A model with just flow was significant ($P = 0.012$; $R^2 = 0.521$).

Table 16. Regression results for ln(R/S) versus mean river flow for Marsh Creek spring chinook salmon.

Brood Years 1973-1990

Model	parameters	estimates	S.E.	P-value	R^2
Flow only	Intercept	-2.446	1.004	0.027	.323
	Flow	0.033	0.012	0.014	
Flow + Spawners	Intercept	-2.118	1.029	0.057	.382
	Flow	0.034	0.012	0.013	
	Spawners	-0.002	0.001	0.253	

Brood years 1975-1985

Model	parameters	estimates	S.E.	P-value	R^2
Flow only	Intercept	-2.924	1.196	0.037	.521
	Flow	0.043	0.014	0.012	
Flow + Spawners	Intercept	-0.357	1.095	0.753	.808
	Flow	0.024	0.011	0.055	
	Spawners	-0.006	0.002	0.009	

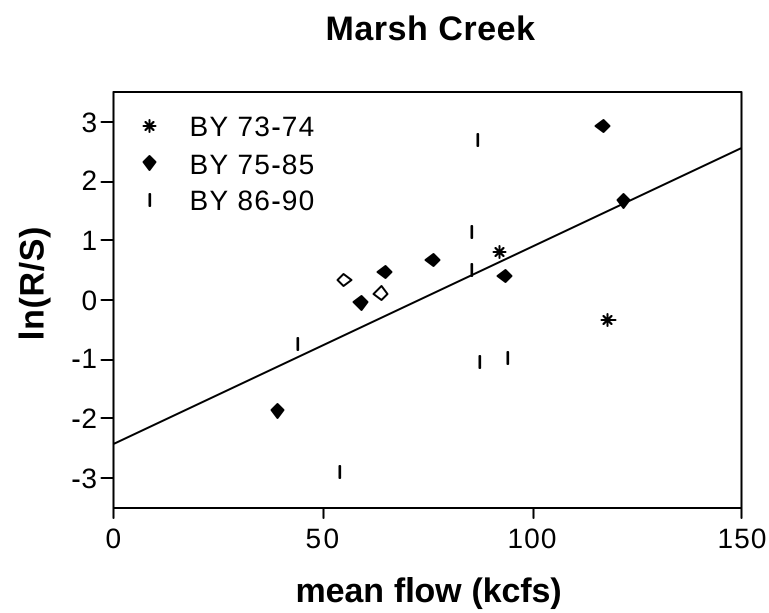


Figure 18. Relationship between natural log recruits per spawner (ln(R/S)) versus mean Snake River flow during the peak migration period for Marsh Creek spring chinook salmon. Flows were measure at Lower Granite Dam over the period April 15-May 5. The line represents a linear regression through the entire data set.

Petrosky (1991) argued that brood years 1973 and 1974 (corresponding to migration years 1975 and 1976) should be eliminated from the analysis because the hydropower system was not operating at full potential and the transportation program was not fully implemented in these years. We conducted an analysis with these years removed, and the results were very similar to those obtained from an analysis of the full time period.

Upper Columbia River steelhead

Raymond (1988) estimated wild steelhead SARs for fish passing Priest Rapids Dam from 1962 to 1984. Cooney (1998) updated these estimates through 1994. Although there is a significant ($P = 0.046$) relationship between these harvest-adjusted SAR estimates and mean April 15 - May 31 flow (Table 17, Fig. 19), the R^2 (0.119) has little predictive value. Also, when only the years since the completion of the hydropower system are included, the relationship becomes weaker and insignificant (Table 17, $R^2 = 0.110$; $P = 0.092$). It is clear, though, that the relationship is not linear (Fig. 19). At seasonal average flows below approximately 125 kcfs and above approximately 180 kcfs, SARs were consistently less than 2%. At intermediate flows, SAR estimates above 2% were observed. Data for hatchery steelhead returning to Priest Rapids Dam (Brown 1995, Raymond 1988) and Wells Dam (Mullan et al. 1992) showed that below average period flows of 125-140 kcfs SARs were almost always less than 2%. At higher flows, SARs ranged from 1 to 7%, generally greater than 1.5% (NMFS 1998).

Table 17. Linear regression results for SAR versus mean river flow for upper Columbia wild steelhead. Regressions were performed over the entire time period (1962-1994) and late period (1975-1995). Flows were measured yearly at Priest Rapids Dam during the period April 15 through May 31.

Period	N	Intercept	(95 % CI)	Slope	(95 % CI)	P	R^2
1962-1995	34	0.00049	(-0.015, 0.017)	0.000106	(0.0000019, 0.00021)	0.046	0.119
1969-1995	27	-0.00026	(-0.019, 0.018)	0.000105	(-0.000018, 0.00023)	0.092	0.110

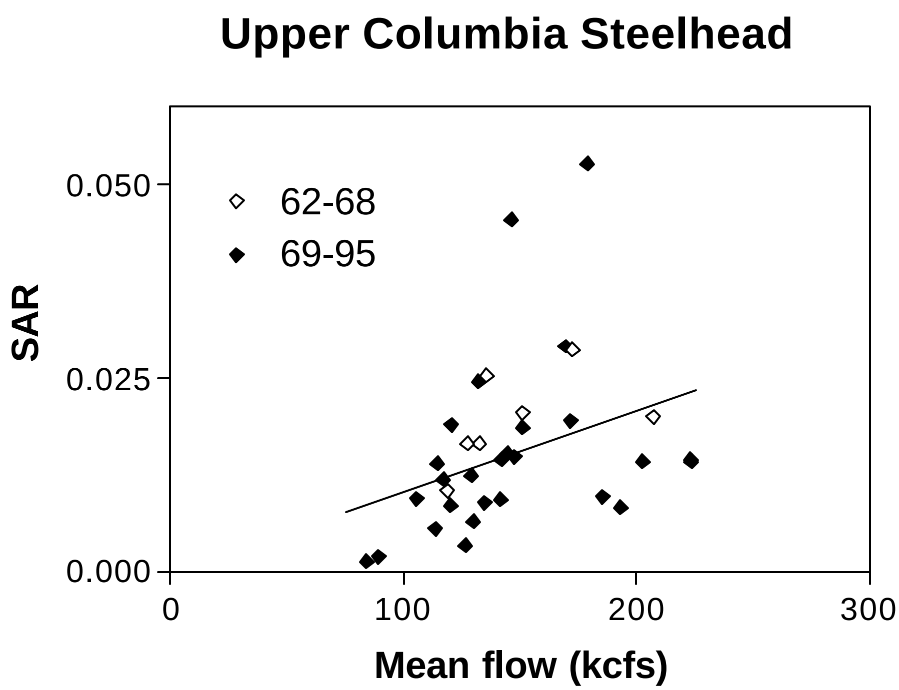


Figure 19. Relationship between smolt-to-adult (SAR) returns, adjusted for harvest, and mean river flow for wild upper Columbia River steelhead for 1962-1995 smolt migrations. Flows were measured at Priest Rapids Dam during the period April 15 through May 31. The line in the plot represents a linear regression for the period 1969-1995.

Fall chinook salmon

Giorgi et al. (1994) found that subyearling chinook salmon migrating through the John Day reservoir early in the summer contributed more adults than juveniles migrating later in the summer for all three years of the study (1981-83). Early fish migrated under conditions of higher flows, lower water temperatures, and lower predation rates. Recoveries of greater than 1% did not occur at less than 200 kcfs and the highest recoveries occurred with average flows greater than 200 kcfs (Fig. 20).

Hilborn et al. (1993) found a significant relationship between flow and adult returns of Priest Rapids fall chinook salmon. However, Skalski et al. (1996), in further analysis, concluded that it was not possible to determine the key factors that influenced these hatchery return rates with the available data and statistical techniques.

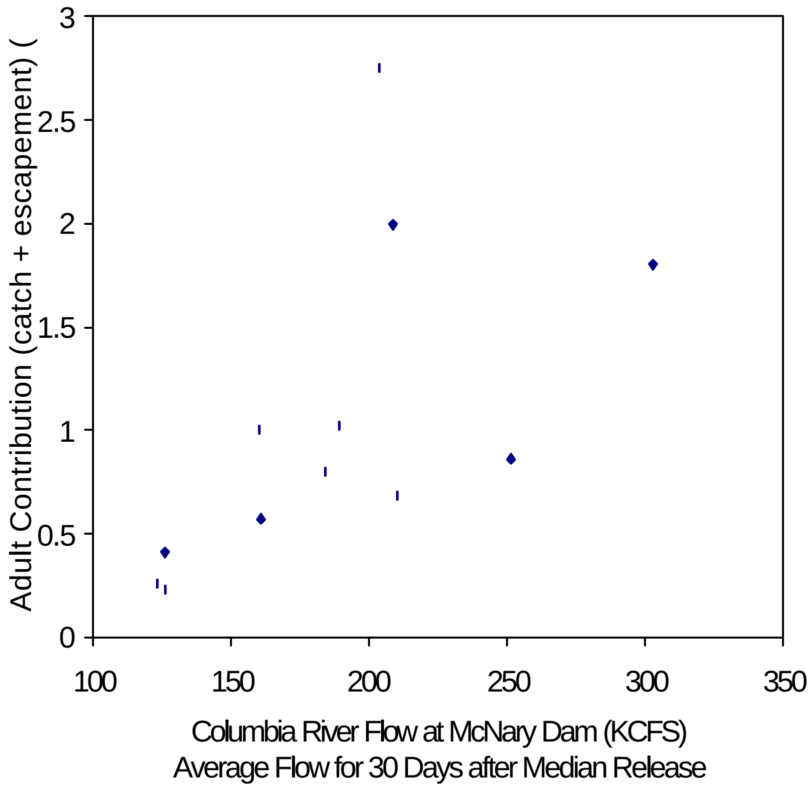


Figure 20. Adult contributions vs. flow at McNary Dam for subyearling chinook salmon outmigrating in 1981, 1982, and 1983 (from Giorgi et al. 1994).

Other species of Pacific salmonids

Other researchers found that increased adult returns of coastal coho occurred following high flow years (Smoker 1955, Scarnecchia 1981).

Conclusions from SAR studies

Some analyses have indicated that a minimum flow in the impounded hydropower system is required for successful adult returns. Petrosky (1991) found that Snake River spring/summer chinook salmon SARs were always low (below approximately 0.1%) when mean Snake River flows were below 85 kcfs during the spring migration (April 20-May 31) and that SARs increased as water particle travel time decreased (Petrosky 1992). When average period flows were above 85 kcfs, SARs were often higher (up to 1.6%). Mundy et al. (1994) also found that low flow conditions in the hydropower system during the juvenile outmigration resulted in low adult returns of Snake River fish. Upper Columbia River steelhead also had low SARs under low flows, but both high and low SARs were observed at higher flows.

While several of these studies suggest a relationship between SAR or ln(R/S) and a measure of flow during the migratory season, these results are difficult to interpret. While measures of adult return rates are important in terms of determining the health of stocks, they are the results of cumulative impacts throughout the salmon's life-history. Because of this, a relationship may be difficult to detect even if it exists. On the other hand, important signals are often confounded in these data sets. As an example, high flow years are also associated with cooler water temperatures and better ocean conditions in the year of ocean entry. Correlation does not necessarily imply causation (Sokal and Rohlf 1981), and higher SARs associated with higher flows does not necessarily indicate that SARs can be increased by adding more flow to the river.

Additionally, since a high proportion of smolts have been transported from the upper Snake River dams to below Bonneville Dam since 1977, an association between SAR and flow for Snake River migrants must reflect either delayed effects of flow conditions experienced upstream from transportation sites or flow conditions experienced in the estuary or Columbia River plume after barge release. However, upper Columbia River spring chinook salmon SARs from the juvenile outmigrations from 1964 to 1984 showed the same trends as those from the Snake River (Raymond 1988), even though the percentage of the juvenile outmigration that was transported from McNary Dam was considerably less than that transported out of the Snake River. Thus, a relationship between adult returns and river flow might be the result of other factors correlated with river flow.

In all cases where studies were updated to remove years before the hydropower system was completed and include more recent data, the newly obtained relationships were weaker than the previously published ones. In some cases, the newly analyzed data set did not contain the full range of water travel time or flows as in previous studies.

One point is abundantly clear from the SAR data: recent SARs have been extremely low as compared to earlier years (pre-1975) for all stocks measured to the point that extinction is a real risk for many stocks (CRI 2000). While it is not possible to establish a clear cause and effect relationship with these data, it is not possible to rule one out. Yearling chinook salmon and steelhead have evolved to migrate during the spring, suggesting that over the evolutionary time scale, spring conditions, including higher river flows, provide an adaptive advantage for survival. Furthermore, variable flows are a natural part of river ecology, benefitting other riverine processes (Stanford et al. 1996, ISG 1996).

Effects on Juvenile Migrant Survival in the Estuary and Near-Shore Environment

The Columbia River plume is a freshwater/seawater interface that provides critical habitat for juvenile salmon survival. The mechanisms by which the Columbia River estuary and plume affect juvenile salmon survival have not been quantified, but likely include provision of food and refuge during transport away from coastal predation. The shape of the Columbia River plume is affected by ocean currents and by the amount of fresh water flowing out of the Columbia River. In addition to flow, the amount of sediment affecting turbidity and the amount of nutrients and organic inputs fueling estuarine and oceanic productivity are likely important to salmon growth and survival.

Water developments in the Columbia River have reduced average flow and altered the seasonality of Columbia River flows and sediment discharge, and have changed the estuarine ecosystem (NRC 1996; Sherwood et al. 1990; Simenstad et al. 1982, 1990; Weitkamp et al. 1994). Annual spring freshet flows (May and June) through the Columbia River estuary are about 70% of pre-development levels, and total sediment discharge is about one-third of 19^{th}-century levels.

Decreased spring flows and sediment discharges have also reduced the extent, speed of movement, thickness, and turbidity of the plume that extended far out and south into the Pacific Ocean during the spring and summer (Barnes et al. 1972, Cudaback and Jay 1996, Hickey et al. 1998). Pearcy (1992) suggested that low river discharge is unfavorable for juvenile salmonid survival despite some availability of nutrients from upwelling, because of: reduced turbidity in the plume (increasing foraging efficiency of birds and fish predators); increased residence time of the fish in the estuary and near the coast where predation is high; decreased incidence of fronts with concentrated food resources for juvenile salmonids; and reduced overall total secondary productivity based on upwelled and fluvial nutrients. Reduced secondary productivity affects not only salmonid food sources but focuses predation by other fishes and birds on the juvenile salmonids.

Finally, due to decreased river flows and development of the hydropower system, many migrant salmon (those not transported) likely arrive in the estuary later than under conditions in which they evolved. Efforts to restore the Columbia River plume toward conditions that existed prior to development of the hydropower system would likely benefit salmonids (ISG 1996). Although the incremental effects of reduced or altered timing of flow from individual tributaries (i.e., the Snake River) in the estuary and near-shore ocean appear small, the cumulative effects are not.

EFFECTS OF FLOW ON ADULT FISH PASSAGE

Adults of all Snake and middle and upper Columbia River salmon species listed under the ESA migrate upstream through the hydropower system during flow management periods. Spring and summer chinook salmon migrate from late March through July; sockeye salmon migrate in June and July; fall chinook salmon migrate from late August through October. Steelhead (all are summer run) migrate from June through October at Bonneville Dam and during the same year from September through November at Lower Granite Dam. In November when water temperatures become quite cold, adult steelhead stop migrating until March through May of the following year (COE 1998).

High spill at dams substantially delays passage of adult chinook salmon (Turner et al. 1983; Turner et al. 1984; Bjornn and Peery 1992). Sometimes high spill levels are involuntary as they result from high flows that considerably exceed powerhouse capacities. Present spring flow objectives in the Snake and Columbia Rivers are at levels (spring: 85-100 kcfs in the Snake, 135 kcfs in the mid-Columbia and 220-260 kcfs in the lower Columbia) that generally do not result in involuntary spill at mainstem dams because powerhouse capacities exceed flow objectives. The one exception is at McNary Dam, where powerhouse capacity is 50 to 90 kcfs less than the flow objectives in spring and summer. However, voluntary spill is provided to increase dam passage survival for juvenile migrants at all dams. In many cases, the spill is provided only at night for juveniles and no spill occurs during the day when nearly all adult passage occurs. In cases where spill is prescribed 24-h per day for juveniles, adult passage delays associated with high spills may occur. When turbine outages occur, flow management to meet the flow objectives may result in flow that exceeds powerhouse capacities, resulting in spill. This rarely occurs. During the summer, lower flows and lower flow objectives (50-55 kcfs in the Snake, 200 kcfs in the lower Columbia) result in little or no spill, thus summer flow management does not affect adult passage.

It is unclear what effect adult delay as a result of spill or flow management has on subsequent stock performance. It is possible that the sum of the negative and positive effects of the hydropower system on upstream migrants is zero. Raymond (1964) compared the median migration timing of sockeye and chinook salmon past Bonneville and Rock Island Dams between 1938 and 1950 when no other dams existed in the hydropower system corridor. The mean difference in passage time between Bonneville and Rock Island Dams of the annual median sockeye salmon passage at each dam was 16.5 days (range 7 to 27 days). We computed the same statistic for the period between 1985 and 1999 and found a mean difference in passage time of 15 days (range 11 to 19 days). Quinn et al. (1997) also studied migration rates of Columbia River sockeye salmon. They found that travel time has decreased in the last 40 years between Bonneville and McNary Dams, but was unchanged between McNary and Rock Island Dams. They also found that river temperatures between McNary and Rock Island Dams actually decreased between 1933 and 1993 and speculated that the reduction in temperatures and reduced water velocities may have resulted in energetic savings. Thus, we conclude from these analyses that delay of adult fish, per se, is not a major issue with the hydropower system and that spill to increase juvenile passage may not seriously impact adults. The caveat to this relates to potential increases in supersaturated atmospheric gas levels that might cause deleterious effects. This issue is addressed in the White Paper on fish passage at dams.

Temperature is an important environmental condition influencing the survival of upstream migrant salmon (Coutant 1970). High temperatures delay entry of salmon and steelhead into the lower Snake River (Stuehrenberg et al. 1978). Maintaining Snake River water temperatures to below 21°C would reduce risk to populations of migrating adult salmon (Dauble and Mueller 1993). Cool water releases from Dworshak Dam have a cooling effect throughout the lower Snake River (Karr et al. 1998). Temperature reductions at Lower Granite Reservoir are strong and almost immediate following release from Dworshak Dam and have lesser affect and occur later at each downstream reservoir (Karr et al. 1998). This thermal inertia also causes the cool water to persist downstream well after releases are discontinued. For example, while Dworshak releases began on July 5, 1994, the greatest temperature reduction did not occur at Ice Harbor Reservoir until August 13, almost two weeks after Dworshak releases were discontinued. Temperature reduction continued for several more weeks and remained below 21 °C throughout the adult migration season. Thus, temperature control primarily aimed at improving conditions for downstream migrant juvenile fall chinook salmon also benefits adult steelhead and fall chinook salmon in the river in July, August, and September.

SUMMARY AND MANAGEMENT IMPLICATIONS

Flow/Travel Time

Recent and past research demonstrates there is a strong flow/travel-time relationship for yearling chinook salmon and steelhead and a lesser relationship for subyearling chinook salmon that migrate in the summer. Travel time of yearling chinook salmon and steelhead tends to decline with date, with increases in flow, and the degree of smoltification. However, subyearling fall chinook exhibit more complex behaviors, as they migrate slowly if at all at body lengths less than about 80 mm and may slow or stop migrating later in the migration season when flows decrease and water temperatures increase.

Flow/Survival

Recent research has not demonstrated a flow/survival relationship for juvenile spring migrants through specific reaches of the lower Snake River (although the highest reach survivals were found during the 1995 through 1998 time period during good flow and high spill conditions). However, consistent and highly significant relationships have been observed between flow and survival for juvenile fall chinook (summer migrants) from release points in the free-flowing portion of the Snake River to Lower Granite Dam. For summer migrants, water temperature and turbidity are also important factors influencing smolt survival. The fact that temperature and turbidity are correlated with survival requires managers to consider both quality and quantity factors when managing flows to benefit this population. Further, although no direct juvenile fish survival benefits were detected through specific reaches of the hydropower system under the good flow and spill conditions that have existed since the implementation of the 1995 BiOp, flows may provide survival benefits downstream from the hydropower system for fish as they migrate through the estuary and into the near-shore ocean environment.

Smolt-to-Adult Returns

Analysis of smolt-to-adult (SAR) returns indicates a relationship between flows and year-class success. Historically, SARs of yearling and subyearling chinook salmon and steelhead were low when mean Snake River, upper (mid-) and lower Columbia River flows during the outmigration periods for these fish were below 85, 135, and 200 kcfs, respectively. These results support management actions to provide flows of at least 85 kcfs in the Snake River and 135 kcfs in the upper (mid-) Columbia River during the spring and 200 kcfs in the lower Columbia River during the summer.

The Estuary and Near-Shore Environment

The development of the hydropower system has had a significant effect on the volume and timing of water entering the Columbia River estuary. The fact that the hydropower system has also significantly altered the timing of juvenile migrants arriving at the estuary supports the rationale to manage flows in the Columbia River toward a more natural hydrograph.

Flow Management

Flow management for the Snake and Columbia Rivers appears to provide salmon survival benefits. However, the benefits are difficult and somewhat speculative to quantify and are not easily demonstrated for every population at all times. This paper demonstrates the benefits of flow management on Snake River fall chinook salmon during selected recent years.

Research conducted since 1995 suggested that the spring flow objectives (Table 2) for the Columbia River are reasonable. They do not provide historical flows or provide conditions that will move juvenile migrants through the area of the hydropower system to the lower river and estuary that matches historical timing. The impoundments create delays which flow management cannot entirely overcome. However, the spring/summer chinook salmon juvenile population that migrates downstream through the hydropower system has survival rates that approach levels measured in the 1960s. This does not imply that smolt survival levels are high enough to ensure recovery for the species, nor does it suggest that flow management is the primary causative agent for this improvement. Rather it suggests that flow management, in conjunction with other fish protection measures, has had a beneficial effect on smolt survival. It should be mentioned, though, that increasing flows in the spring to more closely approximate the historic hydrograph may benefit spring migrants, but allocation of storage water to improve spring flow will likely decrease water available for summer flow to the likely detriment of summer migrants.

Evidence for a survival benefit to fall chinook salmon from flow management is supported by research results. Data sets consistently demonstrated strong relationships between flow and survival, and temperature and survival. The provision of suitable environmental conditions would likely provide substantial survival benefits. The data indicate that benefits of additional flow in the Snake River continue at flows well above those recently observed during a wetter than average hydrologic condition that included the use of stored water to augment flows (but below that observed in 1997 when survival was lower). The ability to substantially increase flow augmentation in the Snake River to benefit these fish is limited and the use of potential sources of water to augment flows in the late summer poses risks as higher water temperature is a concern. However, downstream summer migrants continue to suffer high mortality. Thus, with the existing project configuration and outmigration timing, additional flow augmentation to benefit Snake River fall chinook salmon would likely increase survival.

Overall Conclusions

For spring migrants, a direct relationship between juvenile survival in the hydropower system and flow conditions observed during the 1995 to 1999 study period (flows average to above average and spill at dams as directed in the NMFS 1995 BIOP) could not be established. This does not preclude benefits of flow augmentation during the migration season because increased flows may improve survival outside of the hydropower system as a result of earlier arrival to the estuary, improved estuary conditions, and reduced delayed mortality. SAR and ln(R/S) studies suggest that flow augmentation, particularly at low flows, may benefit cumulative survival of spring migrating stocks. Certainly, increased flows, particularly when base flows are low, will not harm spring migrants. Given the critical levels of many spring migrating stocks, continuing the flow augmentation program is consistent with a "spread the risk" strategy.

Since a migration rate/flow relationship has been established repeatedly for spring migrants, the focus of flow augmentation in the spring should be to decrease travel times and hence shift arrival timing in the estuary closer to historical timing, with the assumption that arrival timing has been under evolutionary control. Studies that detected seasonal trends in travel time/flow relationships suggest that benefits of flow to spring migrants may not be constant throughout the season, and it may be possible to optimize the use of spring flows.

Since some of the hypothesized benefits of flow augmentation occur outside the hydropower system, it would be extremely beneficial to initiate studies to attempt to understand these potential benefits. Questions that need addressing include: Do estuary conditions improve with flow augmentation? Are there measurable effects in factors such as size of the plume, turbidity, or other physical measures at the river/ocean interface Does arrival timing to the estuary confer survival benefits to fish? Is it possible to measure benefits, such as increased growth of earlier arriving fish? Do increased growth rates translate into increased probability of returning to spawn?

For ocean-type chinook salmon, the presence of impoundments, both above and below spawning/rearing areas has greatly impacted their life-history. This presents difficult management challenges because simply restoring conditions toward "normative" conditions may not be effective. It is imperative to understand how ocean-type stocks are responding to current conditions in order to formulate management actions.

A consequence of the shift in rearing habitat and the delay in the initiation of migration is that once subyearling chinook salmon reach the smolt phase and begin active downstream migration, conditions in the reservoirs are highly unfavorable – flows and turbidity are low and temperatures are high. Because of this, subyearling migrants are suffering high mortality while migrating through the Snake and Columbia Rivers.

If modifications to Brownlee Dam were possible to change the temperature of the outflow from the dam, spawning, emergence, and rearing of fall chinook salmon in the Snake River could lead to more historical outmigration timing. Such changes in outmigration timing would substantially improve survival of Snake River juvenile fall chinook salmon as they would migrate downstream under much more favorable flow and water temperature conditions.

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